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UNIVERSITY OF SOUTHAMPTON

FACULTY OF HEALTH SCIENCES

Speech breathing patterns in health and chronic respiratory disease

by

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ABSTRACT

FACULTY OF HEALTH SCIENCES

Thesis for the degree of Doctor of Philosophy

SPEECH BREATHING PATTERNS IN HEALTH AND CHRONIC RESPIRATORY DISEASE

By Rokhsaneh Maria Tehrani

Chronic respiratory diseases (CRD) commonly present with abnormal breathing patterns at rest. There is some limited evidence that breathing patterns during speech (speech breathing patterns), differ in CRD compared to healthy individuals. Monitoring speech breathing patterns could provide useful information about changes in respiratory health, however, little is currently known about speech breathing patterns in CRD. This research aimed to explore and evaluate speech protocols, and characterise speech breathing patterns in health and CRD. Information gathered was taken forward to explore the impact (if any) on speech breathing patterns in patients with CRD before and after Pulmonary Rehabilitation (PR). Respiratory Inductive Plethysmography (RIP) was used to quantify breathing/speech breathing patterns during various speech tasks in three studies. In the first study, 29 healthy adults and 11 adults with self-reported asthma were characterised and speech breathing protocols were evaluated. The second study characterised 20 healthy older adults, and 20 patients with CRD (COPD=14, bronchiectasis=6) were assessed before and after a six week PR programme in the third study. Key novel findings were: 1) Breathing patterns were task specific between speech in healthy younger adults, but this finding could not be generalised to healthy older adults or patients with CRD. 2) Speech breathing patterns differed between health and CRD, but were not disease specific. 3) A recording period of two minutes was sufficient to provide stable breathing parameters 4) Conversational speech was most useful for assessing speech breathing patterns. 5) No changes in speech breathing patterns were observed after PR, but no changes in resting breathlessness or oxygen saturation were observed either. Conclusion: This research has permitted the optimisation of speech protocols for future research and produced new evidence from patient groups that contradicts previous assumptions about task specificity. This research has not produced any evidence to support the hypothesis that speech breathing patterns are responsive to an intervention.

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DECLARATION OF AUTHORSHIP

I, Rokhsaneh Maria Tehrany

declare that the thesis entitled:

Speech breathing patterns in health and chronic respiratory disease

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

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Definitions and Abbreviations

Abbreviation	Definition
AB	Abdomen
%ABInsp	Regional contribution of the abdomen to inspiration
%ABExp	Regional contribution of the abdomen to expiration
ABG	Arterial Blood Gas
AD	Analogue to Digital
ANOVA	Analysis of Variance Analysis
BMI	Body Mass Index
BPM	Breaths per minute
CF	Cystic Fibrosis
CHF	Congestive Heart Failure
COPD	Chronic Obstructive Pulmonary Disease
CoV	Co-efficient of Variation
CRD	Chronic Respiratory Disease
ECG	Echocardiogram
EIT	Electrical-Impedance Tomography
EM	Expiration magnitude
ETCO₂	End expiratory Carbon Dioxide
FEV₁	Forced Expiratory Volume in one second
FVC	Forced Vital Capacity
FEV₁/FVC	Ratio between forced expiratory volume in one second and forced vital capacity

HR	Heart Rate
HRQoL	Health Related Quality of Life
ICU	Intensive Care Unit
IM	Inspiration magnitude
LTOT	Long term oxygen therapy
MCID	Minimal Clinically Important Difference
MRC	Medical Research Council (scale)
<i>n</i>	Number
OAD	Obstructive airway disease
OEP	Opto-Electric Plethysmography
PaCO₂	Carbon Dioxide partial pressure
PEF	Peak Expiratory Flow
PO₂	Oxygen partial pressure
PH	Acid alkaline balance
PNT	Pneumotachograph
PR	Pulmonary Rehabilitation
QDC	Qualitative Diagnostic Calibration
RC	Ribcage
%RCInsp	Regional contribution of the ribcage to inspiration
%RCExp	Regional contribution of the ribcage to expiration
RCT	Randomised Controlled Trial
RDS	Respiratory Distress Syndrome
RIP	Respiratory Inductive Plethysmography

RR	Respiratory Rate
T_E	Expiration time (in seconds)
T_I	Inspiration time (in seconds)
Ti/Ttot%	Proportion of the respiratory cycle devoted to the inspiration phase (expressed as a percentage)
Ttot	Breathing cycle duration (in seconds)
SD	Standard Deviation
SLP	Structured Light Plethysmography
SpO₂	Saturation of oxygen
VAS	Visual Analogue Scale
VC	Vital Capacity
V_T	Tidal volume
WHO	World Health Organisation

Chapter one

Introduction

A brief outline of the contextual framework underpinning this research will firstly be presented, including a justification for the proposal that the use of speech breathing pattern analysis has potential applications in the respiratory monitoring field. A summary of the thesis structure will then be presented.

1.1 Speech breathing pattern analysis – a potential marker of respiratory health?

The global burden of chronic respiratory disease is on the rise, as Chronic Obstructive Pulmonary Disease (COPD) has been projected to become the third leading cause of morbidity and mortality worldwide by 2020 (BTS 2006; Rabe et al. 2007). Amongst the numerous socio-economic repercussions of the disease, acute exacerbations of COPD are one of the most common causes of emergency hospital admissions in the UK, and a third of all adults will be re-admitted within three months (BTS 2006). However, the current approach to managing patients with chronic respiratory disease is based on a reactive system. Emphasis is placed on managing acute respiratory symptoms once they have developed, rather than monitoring changes in respiratory health earlier on. Monitoring would allow changes in respiratory health to be detected **before** respiratory symptoms develop (Morgan 2003), thus potentially reducing costly hospital admissions.

One of the barriers to monitoring respiratory health effectively in a Primary Care setting is the lack of simple, objective respiratory monitoring tools which can sensitively quantify changes in respiratory health over time. Although conventional pulmonary function tests are simple to perform, cost-effective and reliable (Miller et al. 2005; Levy et al. 2009), these tests highlight changes only after significant narrowing of the airways has occurred, and therefore lack sensitivity to small changes (O'Donnell 2000; Miller et al. 2005). Auscultation is a routine component of respiratory assessment which benefits from being

non-invasive, and provides clinicians with valuable information about the function of the lungs (Pasterkamp et al. 1997). However, the interpretation of lung sounds is a subjective practice which is dependent upon the hearing ability of the observer, and whether they are able to discriminate between different respiratory sounds. These drawbacks mean that the interpretation of lung sounds has been associated with moderate to poor inter-rater reliability (Brooks & Thomas 1995; Welsby & Earis 2001). There is therefore a need to develop effective alternatives that can a) quantify small changes in lung health, and b) would be suitable for either a Primary Care or community setting.

Breathing is usually the first vital sign to alter in the deteriorating patient, as changes in breathing pattern can often accompany several respiratory (Ashutosh et al. 1975; Loveridge et al. 1986; Renzi et al. 1986) and non-respiratory disorders (Lieber & Mohsenin 1992). Furthermore, a number of abnormal breathing patterns have been observed in patients with Chronic Obstructive Pulmonary Disease (COPD) (Sassoon & Hawari 1999), bronchiectasis (Koulouris et al. 2003) and asthma (Ritz et al. 2011). It therefore appears that monitoring changes in breathing pattern could provide useful information about changes in respiratory health.

Although major advances have been made into the interpretation and clinical significance of breathing pattern over the past 40 years (Ashutosh et al. 1975; Loveridge et al. 1986; Tobin 1992; Andreas et al. 1996), objective examinations of breathing patterns have yet to translate into routine clinical practice. One of the reasons for this is because monitoring breathing pattern has been challenging. Observation of chest wall expansion, assessing whether a patient is taking deep or shallow breaths, is commonly used for estimating lung volume (Braun 1990). However, this subjective practice has been shown to have poor intra-observer reliability, which is potentially dangerous for patients with low tidal volumes (Tobin 1992). More objective methods are available. The pneumotachograph (PNT) is considered as the gold standard for continuous monitoring of tidal flow (ATS 2003). However, the use of external instrumentation (such as facemasks and mouth pieces) has itself been shown to induce changes in respiratory pattern (Askanazi et al. 1980). Respiratory

Inductive Plethysmography (RIP) has been the most widely accepted non-invasive method for quantifying the parameters of breathing pattern (Chadha & Sackner 1983; Tobin et al. 1983b; Loveridge et al. 1986; Brown et al. 1998). The benefit of this method is that it provides a detailed assessment of the components of breathing pattern from the movements of the chest wall, without the need for invasive facemasks and mouthpieces (Chadha et al. 1982; Cantineau et al. 1992; Poole et al. 2000). However, although this laboratory based technology has been used in numerous experimental studies examining breathing pattern (Tobin et al. 1983c; Chadha et al. 1984; Grossman et al. 2010), extracting these parameters requires complex signal processing techniques, making the technology unsuitable for the clinical environment. Therefore, although breathing patterns can provide useful information about respiratory health, detailed interpretation of breathing patterns has yet to be translated into routine clinical practice because of the challenges associated with analysing them.

At rest, abnormalities in breathing pattern can be difficult to detect, particularly during the early stages of respiratory pathology. Alterations in breathing patterns are usually more pronounced during the later stages of respiratory disease (Sassoon & Hawari 1999; Garcia-Pachon 2002), and are more commonly associated with acute respiratory distress (Kennedy 2007). One way of 'provoking' these abnormalities, even in the early stages of respiratory pathology, is during conditions of high respiratory drive, such as physical exercise (Troosters et al. 2010), or more conveniently, during speech activities (Bunn & Mead 1971).

One of the most noticeable features of respiratory deterioration is the inability to speak in full sentences (Mahler & Wells 1988; Kennedy 2007; Binazzi et al. 2011). While speech and ventilation share the same anatomical structures (i.e. the lungs), in clinical practice these mechanisms are generally thought of as separate entities. 'Speech breathing' research was a major area of interest between the 1970s and 1990s. These exploratory studies were primarily of interest for speech and language therapists (Hixon 1973; Hoit & Hixon 1987; Hodge & Rochet 1989; Winkworth et al. 1994; Winkworth et al. 1995). Since

then, speech breathing research has been a relatively neglected area of research, even though there is some evidence to suggest that speech breathing patterns are different between health and respiratory disease (Loudon et al. 1988; Lee et al. 1993), and a claim has been made that different respiratory conditions produce 'disease specific' breathing patterns (Lee et al. 1993). The detailed examination of speech breathing patterns could therefore provide useful information about respiratory health. However, at present, very little is known about speech breathing patterns in chronic respiratory disease, or how they may alter in response to therapeutic interventions.

This research set out to examine if speech breathing patterns have any potential as a monitor of respiratory health. To that end, research was conducted over three studies. The first study was used to characterise speech breathing patterns in healthy adults, and in adults with self-reported asthma, using more automated methods for extracting speech breathing parameters than have previously been used. This study was also used to determine the optimal speech breathing protocols to use in terms of content and length. The second study characterised speech breathing patterns in a group of older adults, and the third study involved the recording of speech breathing patterns before and after a six week clinical Pulmonary Rehabilitation (PR) programme for patients with COPD or bronchiectasis.

1.2 Thesis overview

This thesis begins with a review of the literature (chapters two, three, four and five), where the clinical significance of breathing/speech breathing patterns is discussed in relation to respiratory monitoring. Chapter six presents the methods, experimental procedures and the plan for statistical analysis employed during the three studies that were conducted with this body of research. This is followed by the results section in chapter seven. In this chapter, the findings from the three studies have been analysed and presented according to six sections, that is:

- 1) Speech breathing patterns in healthy young adults,
- 2) Speech breathing patterns in healthy older adults,
- 3) The influence of age and sex on speech breathing patterns in healthy adults,
- 4) Speech breathing patterns in patients with diagnosed chronic respiratory disease,
- 5) Comparison of speech breathing patterns between:
 - a) healthy younger adults vs healthy older adults
 - b) healthy younger adults vs adults with self-reported asthma
 - c) patients with COPD vs patients with bronchiectasis
 - d) healthy older adults vs adults with COPD or bronchiectasis, and
- 6) Speech breathing patterns before and after a six week PR programme in patients with COPD or bronchiectasis.

A discussion of the findings in relation to the existing literature and study limitations has been presented in chapter eight. Finally, research conclusions and plans for future research are presented in chapters nine and ten respectively.

Chapter Two

Breathing pattern: Clinical significance and implications for respiratory monitoring

Introduction

This chapter begins with a review of some of the common methods currently used to monitor respiratory health in Primary Care. An understanding of the breathing patterns associated with respiratory disease requires sound knowledge of what constitutes normal breathing pattern. In this chapter the definition of 'normal' breathing pattern is therefore discussed. This will be followed by a review of some of the characteristic breathing patterns associated with respiratory pathology, and the complexity faced with monitoring them. Finally, a justification for the use of RIP in the current investigation, and the procedures used for calibrating RIP will be discussed respectively.

2.1 Tools for monitoring chronic respiratory disease in Primary Care

'Monitoring', which is derived from the Latin word *monere* (meaning 'to warn'), has a number of applications in the respiratory field, including the identification of significant changes in respiratory health, aiding with diagnosis and determining the efficacy of treatments (Cohen 1992b; Folke et al. 2003; Yañez et al. 2012). Advances in respiratory monitoring techniques in recent decades have generally benefited from being objective, cost effective and simple to perform. However, the value of being non-invasive and unobtrusive has become increasingly recognised in the Primary Care and the community setting. The next section will consider some of the most commonly used respiratory monitoring tools in Primary Care for detecting changes in respiratory health.

2.1.1 Spirometry

Lung function parameters in relation to volume and flow are frequently used as a basic diagnostic and classification tool for a number of respiratory diseases (Miller et al. 2005; Wise 2006; Rabe et al. 2007). In particular, spirometry is a method for examining lung function by measuring the volume of air that can be forcefully expelled in one second after a maximal inhalation (FEV₁) (Miller et al. 2005). The widespread application of spirometry has also been used to determine the efficacy of a number of therapeutic interventions (Enright et al. 1994; O'Donnell 2000). With appropriate training, spirometry has been praised for being simple to perform, while providing a rapid and valid measure of lung health (Levy et al. 2009). However, these advantages only apply if the test has been appropriately performed. Spirometry is effort dependant, and relies on the training of the administrator as well as the co-operation of the patient (Miller et al. 2005). Poorly performed tests can often lead to misinterpretation of results, which may lead to the generation of inappropriate diagnosis (Levy et al. 2009).

In UK GP practices the availability of spirometry has markedly increased over the past two decades, as manufacturers have made these devices small and portable, and lung function testing has become standardised for the diagnosis of COPD (Celli et al. 2004; Miller et al. 2005; GOLD 2014). Forced Vital Capacity (FVC) and Forced Expiratory Volume in one second (FEV₁) are the most useful parameters for detecting airway obstruction, where post bronchodilator FEV₁ is the single most important parameter for determining the severity of airways obstruction in COPD (Wise 2006; Rabe et al. 2007; GOLD 2014). However, while spirometry testing has been routinely used to inform clinical decision making, interpreting lung function parameters in isolation has limited clinical value.

In COPD, spirometry can only be used to confirm a diagnosis in the presence of other clinical signs and symptoms, such as breathlessness, increased sputum production and reduced exercise capacity (Rabe et al. 2007; GOLD 2014). Furthermore, lung function measurements do not always correlate with

clinically relevant symptoms, like breathlessness and functional exercise capacity (Wise 2006; Cazzola et al. 2008). This is because, in COPD, the disease is typically diagnosed in the later stages of the natural progression, once there has been considerable narrowing of the airways, and patients are generally asymptomatic in the earlier stages of the disease (Rabe et al. 2007). In addition, improvements in patient reported outcomes following Pulmonary Rehabilitation have been found to be independent of changes in lung function (Niedermaier et al. 1991). These findings suggest that there can be a ‘mismatch’ between objective lung function findings and clinical signs and symptoms.

Despite the diagnostic value of spirometry and its widespread application in classifying the progression of COPD in a Primary Care setting, it appears that spirometry has limited application in the daily monitoring of respiratory disease, primarily because the measure lacks sensitivity to small changes in the airways. Practical drawbacks also reduce the value of spirometry for use in long term monitoring. The measure is dependent on a number of technical and personal factors, which need careful consideration when performing the tests and interpreting the findings.

2.1.2 Peak Expiratory Flow

Peak Expiratory Flow (PEF) is the maximum flow rate of air which is reached during a forced expiration manoeuvre, after full inspiration (Lebowitz 1991; NICE 2015). The measure has potential to be a useful monitor of asthma in Primary Care as it reflects a range of physiological characteristics of the large airways including; elastic recoil, lung volume and neuromuscular integrity (Quackenboss et al. 1991). Like spirometry, the procedure is effort dependant and requires the individual to take a maximum inspiration, make a tight seal around the mouth piece and then breathe out with a rapid forced expiration. In practical terms, the PEF meter is inexpensive, portable and easy to use (Lopez & Del Castillo 2000).

Traditionally, PEF measurement has been used in the management of asthma to a) aid diagnosis b) assess severity and c) to help identify provocative factors

(Jamison & McKindley 1993). In particular, large within day variability of PEF measures are known to be associated with severe asthma attacks, and increased mortality (Cross & Nelson 1991; Lebowitz 1991; Hansen et al. 2001). A within day variability of more than 20% has been suggested to be typical of asthma (Jamison & McKindley 1993; NICE 2015) and PEF variability has been shown to correlate with bronchial reactivity to histamine methacholine in patients with asthma (Parameswaran et al. 1999). The theoretical advantage of monitoring PEF daily is that the measure can provide clinicians with rapid, daily information about the function of lungs, which is objective and simple to obtain.

Although PEF has made a major contribution to the management of asthma (NICE 2015), the advantages of monitoring PEF in patients with other chronic respiratory diseases, like COPD, are less clear. Clinical guidelines for the management of COPD are explicit in advising the use of the ratio of FEV₁/FVC and the percentage of FEV₁ rather than PEF in the ongoing monitoring of COPD (NICE 2010; BTS 2013; GOLD 2014). In patients with COPD, the relationship between FEV₁ and PEF has been shown to be poor (Nolan & White 1999; Llewellyn et al. 2002). While PEF reflects changes in lung characteristics, this information is limited to the large airways. FEV₁ provides additional information about the function of the small airways, which become progressively damaged throughout the natural progression of COPD (Nolan & White 1999). Therefore, doubts concerning the usefulness of PEF over FEV₁ relates back to the information that they each provide.

Unlike PEF which measures peak expiration within the first 10th of a second, FEV₁ continues to record forced expiration for a further 0.9 seconds. FEV₁ therefore records additional information about the expired air once PEF has been reached. Characteristics of COPD are highlighted during this component of the forced expiration manoeuvre and clear differences can be observed between health and disease (Llewellyn et al. 2002). In healthy individuals, forced expiration produces a steady decline over time. However the decline in patients with COPD is more sudden, as forced expiratory flow drops as soon as PEF is reached. Physiologically, reductions in lung parenchyma leading to

reduced elastic recoil have been identified as the cause responsible for this sudden drop in expiratory flow (Lokke et al. 2006). These characteristics can be evaluated with spirometry, but not with PEF, because changes in PEF are usually only observed in the severe stage of COPD (Perez-Padilla et al. 2009). In patients with COPD, the decline in lung function is usually so slow that PEF is unlikely to provide significantly new information more than every one to two years (Nolan & White 1999)

PEF and spirometry provide useful information about the global calibre of the airways during a single maximal effort breath, but are both insensitive to small changes in lung health.

2.1.3 Auscultation

Breath sounds potentially contain a wealth of information about airway geometry, ventilation and pathology (Pasterkamp et al. 1997). Using a stethoscope it is possible to detect the presence of secretions (Ceresa & Johnston 2008), consolidation (Metlay et al. 1997) and effusion (Rolston et al. 2008), which can sometimes make redundant the need for more technical equipment such as chest radiography. In respiratory physiotherapy, lung sounds are usually examined either during the routine assessment of patients at baseline, in response to a clinical intervention, or over time (Ceresa & Johnston 2008). Unlike spirometry, the analysis of lung sounds does not require maximal breathing effort, and therefore requires minimal participation from the patient. This is a particular advantage for patients who are critically ill, or who are unable to follow instructions. Auscultation benefits from being simple to perform and cost effective (Pasterkamp et al. 1997).

Breath sounds heard at the chest surface with a stethoscope are thought to be directly related to structural changes in the lungs. In patients with emphysema, dampened breath sounds have been linked with airflow limitation (Schreur et al. 1992). The presence of crackles has been associated with a number of respiratory (Baughman et al. 1991; Piirila & Sovijarvi 1995) and non-respiratory disorders (such as cardiovascular failure) (Kataoka 2007), and have been

described as discontinuous adventitious sounds, explosive and transient in character (Piiirila & Sovijarvi 1995; Vannuccini et al. 1998). The generation of crackles has been subjected to a number of theories. Originally, crackles were thought to derive from the bubbling of air through secretions, or the motion of secretions through the airways (Murphy, 1985). However, this theory was disregarded following the observation that crackles may not always disappear after coughing. It is now generally believed that crackles are generated through the sudden opening of abnormally closed airways (Forgacs et al. 1971).

Despite the information that lung sounds can provide, discriminating between different breath sounds heard through a stethoscope can be difficult. Crackles for example, have short durations and are low in intensity, which can make them challenging to hear (Vannuccini et al. 1998). The interpretation of breath sounds heard through a stethoscope depends of a number of personal factors: 1) the sensitivity of the ear to different sound frequencies depends on the relative loudness of the sound 2) the ability of the ear in recognising short duration sounds and 3) the ability of the ear to distinguish between sounds that are separated by short intervals (Sovijarvi et al. 2000). Interpreting breath sounds is therefore a subjective practice which purely depends on the hearing ability of the observer.

Due to subjectivity of auscultation, the inter observer reliability has been shown to be poor to fair between physiotherapists (Brooks et al. 1993; Brooks & Thomas 1995; Allingame et al. 1997). However studies examining whether training experience influences the reliable interpretation of breath sounds have reported no inter-group differences (Brooks et al. 1993; Allingame et al. 1997). Allingame *et al* (1995) examined the effect of clinical experience on the reliable interpretation of a number of auscultated breath sounds by comparing the findings from 16 new physiotherapist graduates and 16 experienced respiratory physiotherapists. The definition of an 'experienced' physiotherapist was not described, and the duration of their clinical experience was not specified. Participants were invited to listen to six characteristic breath sounds played through a tape recorder, where each of the six sounds were repeated three times in a random order, so that intra rater reliability could also be

examined probabilistically using Fishers exact test statistic. Intra-rater reliability was found to be poor for each of the breath sounds examined, as a maximum of nine participants (from both groups) recorded the same response on all three occasions (28%). However, when examining between the two groups (graduate v experienced physiotherapist), no significant differences were found for any of the breath sounds examined ($p < 0.05$). Despite these findings, research examining the reliability of interpreting auscultated breath sounds through a stethoscope is methodologically flawed. For practical reasons, the breath sounds were played through a tape record within a laboratory environment (Brooks et al. 1993; Allingame et al. 1997). This provides a limited representation of a natural setting; auscultation is usually conducted in open clinical areas, where external sounds could further influence the interpretation. These implications have not been considered in existing studies examining the reliability of interpreting breath sounds through a stethoscope.

In light of these subjective problems, standard auscultation appears to have limited value for the objective monitoring of respiratory health, or for being used as an outcome measure following a therapeutic intervention.

2.1.4 Oxygen saturation

Arterial oxygen saturation (SaO_2) is the percentage of oxygen reversibly bound to haemoglobin in arterial blood and provides some information about the adequacy of gas exchange within the lungs. The taking of arterial samples is painful and invasive, so is not suitable for long term monitoring within community settings. A surrogate for arterial sampling is the use of pulse oximeters to measure arterial oxygen saturation (SpO_2) noninvasively using light emitting diodes (Yelderman & New 1983). Bone, tissue, pigmentation, and venous vessels normally absorb a constant amount of light over time. Oxyhaemoglobin and its deoxygenated form have significantly different absorption pattern (Schnapp & Cohen 1990). The arteriolar bed normally pulsates and absorbs variable amounts of light during systole and diastole, as blood volume increases and decreases (Mendelson 1992). The ratio of light

absorbed at systole and diastole is translated into an oxygen saturation measurement using complex algorithms. Healthy individuals should maintain their SpO₂ between 95-100% in order for the surrounding tissues to remain adequately oxygenated (Wukitsch et al. 1988).

Monitoring of arterial oxygen saturation using pulse oximetry has had a number of clinical applications including in the intensive care setting (Jubran 1999; Grap 2002), as an outcome measure following therapeutic interventions (Giardino et al. 2004) and for monitoring respiratory health during treatments, such as Long Term Oxygen Therapy (LTOT) (Sliwinski et al. 1994; Garrod et al. 2000; Tang et al. 2012; Minami et al. 2014). However, while oxygen saturation is a useful indicator of clinical deterioration when considered in combination with other clinically relevant physiological changes (such as respiratory rate, heart rate, temperature and blood pressure), the use of oxygen saturation to monitor changes in respiratory health has limited application when considered in isolation.

Studies have repeatedly demonstrated that levels of oxygen saturation fluctuate between day and night, as well as during different activities of daily living in patients with COPD (Soguel Schenkel et al. 1996; Casanova et al. 2006; Takigawa et al. 2007; Minami et al. 2014). In patients with COPD, changes in oxygen saturation are reflective of physical activity as well as changes in health status, and it is difficult to differentiate the two. The evidence examining the use of oxygen saturation as a predictor of COPD exacerbation is both limited and conflicting, however the majority of the research has agreed that the examination of oxygen saturation in isolation is a poor predictor of prognosis in patients with COPD (Trauer et al. 2013; Minami et al. 2014).

To date, only one study has reported that desaturation profiles may predict prognosis in patients with COPD (Takigawa et al. 2007). These findings were observed in patients with COPD during a six minute walk test (6MWT). However, field tests such as the 6MWT have primarily been criticised for their inability to reflect activities of daily living, because the majority of these

activities are conducted during submaximal levels of effort. The assessment of oxygen saturation during field tests such as the 6MWT may not be satisfactory in gaining an actual understanding of oxygen profiles in patients who have COPD. As a consequence, recent studies investigating the use of oxygen saturation as a predictor of COPD exacerbations have been conducted over a 24 hour period, during activities of daily living (Trauer et al. 2013; Minami et al. 2014).

Minami *et al* (2014) found no evidence that the frequency of oxygen desaturation predicted the risk of exacerbation in 51 patients with COPD. Ambulatory oxygen saturation was monitored using a portable pulse oximeter over a 24 hour period for each participant. Exacerbations and mortality were then recorded during a mean follow up period of 26.4 months. In support of previous findings that greater desaturations occur at night in patients with COPD, changes in oxygen saturation varied significantly between day (3% were below 90% saturation) and night (7% below 90% saturation). In total, 21 exacerbations were reported in 13 patients during the mean follow up period and univariate and multivariate Cox proportional hazard analysis did not detect any significant factors associated with exacerbation (risk ratio 1.01; 95%CI=0.92-1.11; p= 0.78). These findings were also in broad agreement with Trauer *et al* (2013). One of the most likely explanations for this lack of association could be because COPD is a heterogeneous condition with various different clinical manifestations which vary between individuals and differ according to the severity of the disease (GOLD 2014).

In practical terms, the quality of SpO₂ measurements depends on the ability of the pulse oximeter to distinguish between the oxyhaemoglobin and deoxyhaemoglobin, which can be affected by movement and poor circulation (Biebuyck et al. 1992). Studies examining the possibility of using pulse oximetry for home monitoring have generally been limited as they have involved healthy participants who a) had no history of cardiovascular or circulatory problems, and b) were young (Tang et al. 2012). In a patient population, circulatory problems and increased age can impair the accuracy of the measurement (O'Driscoll et al. 2008). Other factors include the use of nail

varnish, skin pigmentation and excessive movement (Taylor & Whitwam 1986; Ralston et al. 1991). Although SpO₂ and SaO₂ are closely correlated in healthy individuals and in some patient groups, it has been reported that factors like anaemia and acidosis can affect this relationship. A study of critically ill patients concluded that changes in SpO₂ do not reliably predict equivalent changes in SaO₂ (Perkins et al. 2003)

In conclusion, arterial oxygen saturations via pulse oximeters provide useful information about gas exchange, and are valuable for titrating oxygen supply, or indicating sudden, severe respiratory compromise. Pulse oximeters have some limitations, however, and are less useful for detecting small changes in respiratory function.

2.1.5 Summary

Despite the steady rise in emergency hospital admissions from exacerbations of acute respiratory symptoms (BTS 2006; Connolly et al. 2006), detecting early changes in respiratory health within a Primary Care setting is challenging, as all current methods used to monitor respiratory health are associated with a number of limitations. There is generally a compromise between the information that a tool provides, and the practicalities encountered when obtaining or analysing the measure.

A number of respiratory diseases commonly present with abnormal breathing patterns (Tobin et al. 1983b; Brack et al. 2002; Brack et al. 2007), and it is possible that the detection/measurement of these abnormalities might serve as a useful indicator of respiratory health. The next part of this chapter will introduce breathing patterns with particular reference to their applications in monitoring respiratory health.

2.2 Breathing pattern

2.2.1 Introduction

In respiratory physiotherapy, simple observational assessments of breathing pattern have been useful for examining respiratory status at baseline (Tobin et al. 1983b; Sassoan & Hawari 1999). Alterations in breathing pattern can signify respiratory deterioration (Hoover 1920; Loveridge et al. 1986; Kennedy 2007), however breathing pattern itself is a generic term with no consensus regarding its definition, and various respiratory parameters have been used to characterise 'normal' breathing pattern in the medical literature.

Some elements of breathing patterns have been described as absolute measures, such as indices relating to timing, volume and flow (Askanazi et al. 1980; Tobin et al. 1983a; Loveridge et al. 1986), whereas other parameters of breathing pattern have historically relied on subjective interpretation, such as characteristic breathing rhythms (Lieber & Mohsenin 1992; Brack et al. 2007), and chest wall contributions (Ashutosh et al. 1975). Breathing pattern is therefore an ill-defined area of research because the term incorporates a number of different breathing parameters, some of which are challenging to measure objectively, even though they may provide useful information about respiratory health (Tobin et al. 1983b). The next section will consider some of the aspects of breathing pattern in health.

2.2.2 Aspects of breathing pattern in health

Healthy breathing pattern is largely independent of the use of accessory muscles and should be effortless (Tobin et al. 1983a). Resting healthy breathing pattern is a rhythmic process comprising of an active inspiratory expansion phase, followed by a passive relaxation of the rib cage at a relatively constant rate (Walker 1990). The clinical utility of any physiological measure is largely dependent on its ability to differentiate between normal and abnormal. However, unlike other measures of respiratory performance, which have internationally agreed limits and published normative data (such as lung

function, oxygen and carbon dioxide levels), limits for the parameters of normal breathing pattern have never been rigidly defined. A significant proportion of breathing pattern research has so far been based upon findings from small observational studies (Tobin et al. 1983b; Loveridge et al. 1986; Alves et al. 2008), where there has been considerable variability in terms of methodological design. As a consequence, the majority of breathing pattern parameters have yet to be used in routine clinical practice, outside of critical care environments.

2.2.2.1 Tidal volume

Tidal volume refers to the volume of air displaced during inspiration and expiration. Resting tidal volume is the volume of air displaced during quiet breathing at rest. Examinations of tidal volume have can be based on breath-by-breath analysis (Gilbert et al. 1972; Tobin et al. 1983a; Kuratomi et al. 1985), but more commonly tidal volume is determined from the average of a collection of breaths obtained over various time periods (Tobin et al. 1983a; Semmes et al. 1985; Tobin 1992; Parreira et al. 2010). During resting tidal breathing, the lungs have been shown to remain ‘moderately’ inflated throughout the inspiration and expiration phase for each breathing cycle. The lungs are never fully inflated or deflated at maximal capacity during tidal breathing, as this would involve additional respiratory effort. Anatomical build (Parreira et al. 2010), age (Prihan 1963; Tobin et al. 1983a), sex (Parreira et al. 2010), and positioning (Verschakelen & Demedts 1995) are known to influence tidal volume in healthy adults, and as a consequence, a large variety of ‘normal’ ranges have been documented in the literature. An overview of some of these variations are presented in table 1.

Study	Sample size	Measurement instrument	Age	Sex	Tidal Volume
Tobin <i>et al</i> (1983)	47	RIP	18-60	Both	383±85ml
	18		60-81		382±109ml
Landers <i>et al</i> (2003)	30	PNT	23	Both	630±60ml
Dellweg <i>et al</i> (2008)	10	PNT	33	All male	510±20ml
Parreira <i>et al</i> (2010)	48	RIP	29-39	Male	441±114ml
			29-39	Female	325±127ml
	18		40-59	Male	325±115ml
			40-59	Female	309±111ml
	38		60-80	Male	383±124ml
			60-80	Female	283±85ml

RIP = Respiratory Inductive Plethysmography, PNT = Pneumotachograph

Table 1: Summary of the main studies documenting tidal volumes in healthy adults

Based on studies presented in table 1, the major sources of variability in tidal volume can be attributed to sex, age and the instrument used to obtain the parameter. In general, the basis for sex related differences in pulmonary function has been broadly categorised as hormonal and structural/ morphological differences (Fleischer *et al.* 1985; Verschakelen & Demedts 1995; Carey *et al.* 2007). Structural differences have been thought to account for the observed differences in tidal volume between males and females, as the diameter of the airways and thoracic length have been shown to be longer in males (Thurlbeck 1982). As a consequence, adult females tend to have smaller tidal volumes (Carey *et al.* 2007).

It has been suggested that increasing age is associated with decreased tidal volumes (Tobin et al. 1983a; Hoit & Hixon 1987; Parreira et al. 2010). These differences have been largely attributed to decreased lung compliance and elastic recoil with the progression of age, as studies have repeatedly demonstrated a positive correlation between increasing age and reduced lung elastic recoil (Turner et al. 1968; Janssens et al. 1999). Physiologically, reductions in lung elastic recoil limit the ability for the lungs to draw in or expel air during the inspiratory and expiratory phase, thereby 'restricting' tidal volume to a narrower range.

One of the most prominent sources of variability for tidal volume is the instrument used to obtain the parameter. Studies that have used a pneumotachograph (PNT) to measure tidal volume have consistently reported larger tidal volumes compared to those that have used non-invasive instruments, such as Respiratory Inductive Plethysmography (RIP). Respiratory monitoring systems will be examined in more detail in section 2.3.5, but it has been shown that the use of mouth pieces and facemasks are associated with increases in tidal volume (Askanazi et al. 1980; Perez & Tobin 1985). Alteration of the natural route of breathing and its associated discomfort has been thought to be the main cause (Perez & Tobin 1985). As a consequence, instrument induced changes in breathing pattern occur when tidal volume is obtained using a PNT, even though the PNT is considered to be the gold standard for the measurement of volume and flow. Studies using non-invasive respiratory monitoring tools could potentially provide a more realistic reflection of the actual tidal volume, as the system does not alter the natural route of breathing.

2.2.2.2 Respiratory timing components

Respiratory rate is one component of breathing pattern which has been widely used during clinical monitoring (Fiesemann et al. 1993; Yañez et al. 2012). Regulation of arterial pH within narrow limits (between 7.35 and 7.45) relies on the maintenance of an optimal respiratory rate (Singer & Hastings 1948). A wide range of respiratory rates have been documented for healthy adults at

rest. In an early study by Dejours (1966), extreme variations of respiratory rate were measured in resting healthy adults (5-22 breaths per minute (bpm)). However, these findings were recorded during observational assessments of chest wall movements over a one minute period. The limitation of this technique is concerned with the subjectivity associated with visual inspection (section 2.3.1). More recent physiology text-books consider the average respiratory rate to be 14bpm (Hough 2001). These observations suggest that there is intra-individual variation, even within a healthy population.

2.2.3 The complexity of breathing pattern

Breathing is an unusual function that is under both voluntary and involuntary control, as it is governed by the sympathetic and parasympathetic nervous system (Homma & Masaoka 2008). While breathing is predominantly regulated by the brain stem and is responsive to metabolic demand, it is well known that breathing is also responsive to psychological and behavioural changes including emotion, fear and anxiety (Gomez & Danuser 2004; Homma & Masaoka 2008). Breathing is also under voluntary control within specific boundaries; for example it is possible to hold your breath on impulse, but only for a finite period of time. Breathing patterns are therefore determined through a complex interaction between cognitive and autonomic factors.

In adults, anxiety has been associated with irregular breathing patterns (Tobin et al. 1983b), shorter expiratory times and increased respiratory rate (RR) (Masaoka & Homma 1999). Respiratory rate has also been shown to increase in the presence of anger (Dudley & Pitts-Poarch 1980) and in response to mental stress induced by loud noise and sound pressure (Masaoka & Homma 1997). The interpretation of breathing patterns can therefore be challenging, as they are not always representative of respiratory drive, because breathing is also influenced by behavioural factors. Fear and anxiety are emotions that are frequently experienced by hospitalised patients, particularly those awaiting surgery (Graham & Conley 1971). These emotions are rarely taken into consideration when assessing breathing pattern. The majority of available breathing pattern data have been obtained in manipulated clinical

environments, with few data available in a naturalistic community setting (Grossman et al. 2010).

There is also an agreement that even the use of non-invasive respiratory monitoring devices (such as RIP) can alter spontaneous breathing pattern through 'awareness' (Gilbert et al. 1972; Western & Patrick 1988; Han et al. 1997). Western and Patrick (1988) examined the influence of awareness on changes in breathing patterns in 18 healthy male participants. Respiratory Inductive Plethysmography was used to record breathing pattern by fastening two bands around the rib-cage and abdomen (section 2.3.8). Breathing patterns were recorded during two periods of interest, that is, a distraction period and an awareness period, each lasting five minutes. During the distraction period, participants were misinformed that the Inductobands (see section 2.3.8) were for electrocardiographic (ECG) monitoring (and not respiratory monitoring). Participants were then equipped with headphones and asked to listen to a story with the aim of distracting their attention away from the recording session. For the second condition, participants were verbally told that their breathing patterns were being closely recorded using the Inductobands. Although it is not clear whether the headphones were enough to distract participants' attention away from their breathing, the study reported a statistically significant increase in inspiratory and expiratory time during the awareness state compared with the distraction period. These findings highlight the possible influence of measurement awareness on breathing pattern. However at present, it is not known if these differences were large enough to be of any clinical importance.

Even though some elements of breathing pattern appear to have a high level of inter-individual variability, there is some evidence to suggest that breath-by-breath variations in breathing pattern are consistent within individuals over time. Shea *et al* (1987) examined the reproducibility of some elements of resting breathing pattern within individuals using RIP. Forty one healthy adults were involved in the study where tidal volume, inspiration and expiration time, respiratory rate and the proportion of time spent on inspiration (expressed as a percentage), were all recorded four times for five minutes each over the

course of two days. However, the time intervals between these recordings were not defined, and it is not clear whether the recording intervals were standardised for each participant. Between and within group differences were examined using Fishers F variance ratio, derived from analysis of variance (ANOVA), where the results demonstrated that the differences between individuals were significantly greater than the differences within individuals (Shea et al. 1987). However, these results were based on the analysis of only 24 consecutive breath cycles for each recording session, and it was not clear how these were selected. Other elements of breathing pattern, such as breath-to-breath variability and ribcage and abdomen contributions were not studied. Despite these limitations, these findings suggest that some components of breathing pattern may be stable within individuals, and therefore could be useful for monitoring respiratory health over time. The majority of breathing pattern research has been limited to examining breathing patterns in healthy individuals on a single occasion.

In summary, even though there is some evidence to suggest that breathing patterns are consistent over time within individuals, resting breathing pattern can be influenced by a number of behavioural and emotional factors (Dudley & Pitts-Poarch 1980; Boiten et al. 1994; Masaoka & Homma 1997). These findings highlight the complexity associated with interpreting resting breathing patterns in healthy individuals, which could account for why detailed interpretation of resting breathing patterns has yet to be translated in to routine clinical practice. The next section will consider some of the changes in breathing patterns in patients with respiratory impairments.

2.2.4 Aspects of breathing pattern in chronic respiratory disease

In the past 40 years breathing pattern has been subject to extensive investigation regarding its interpretation and clinical significance, as alterations in many different respiratory variables have been studied in relation to respiratory impairment (Dejours 1966; Ashutosh et al. 1975; Tobin et al. 1983b; Loveridge et al. 1986; Andreas et al. 1996). It has been suggested that careful inspection of changes in breathing pattern can help to inform diagnosis

and determine the effectiveness of therapeutic interventions (Hough 2001). Breathing patterns in patients with chronic respiratory disease have been studied previously, with the majority of these studies involving patients with COPD (Hoover 1920; Loveridge et al. 1986; Loring et al. 2009).

The next section will consider some of the most significant breathing pattern abnormalities observed in patients with chronic respiratory disease.

2.2.4.1 Alterations in chest wall mechanics

2.2.4.2 Synchrony between the ribcage and abdomen during tidal breathing

Movements of the chest wall during respiration have been described for healthy individuals (Tobin et al. 1983a) and in patients with respiratory disease (Ashutosh et al. 1975; Tobin et al. 1983b; Loveridge et al. 1986). In healthy adults, there is an agreement that the displacements of the ribcage and abdominal components are synchronised with every breath, where the ribcage and abdomen are both displaced outwards during inspiration. (Campbell 1964; Konno & Mead 1967; Ashutosh et al. 1975; Troyer & Estenne 1984; Maitre et al. 1995). It is understood that this occurs because the downward movement of the diaphragm during inspiration displaces the abdominal contents in an outward motion, while the rib-cage simultaneously elevates (Ashutosh et al., 1975, Campbell, 1964).

Changes in chest wall movements have been reported in patients with respiratory disease. Lack of co-ordination between the ribcage and abdominal compartments was first documented in the in 1920s by Charles Franklin Hoover, who observed that the paradoxical inward drawing of the costal margins at the end of inspiration occurred in patients with what was then called 'Obstructive Airways Disease' (OAD) (Hoover 1920). 'Hoover's sign' has since been interpreted to indicate the flattening of the diaphragm secondary to hyperinflation in patients with OAD (White et al. 1995). However, while Hoover's sign has not been formally examined in relation to diaphragmatic function, there is evidence to suggest that the detection of breathing

asynchrony in patients with what is now called chronic obstructive pulmonary disease (COPD), is associated with a poorer prognosis compared to those who do not have asynchrony. Ashtoush *et al* (1975) examined chest wall movements using magnetometers (a pair of coils attached to the anterior and posterior body surface), in 30 patients with COPD, where 13 were identified to have asynchronous breathing using Hoover's sign. Compared to the patients with no identifiable asynchrony, the 13 patients with breathing asynchrony had a significantly lower Forced Vital Capacity (FVC), with 10 of these patients being dependant on assisted ventilation.

There is also evidence to suggest that the detection of breathing asynchrony is more prevalent in patients with advanced COPD, as Garcia-Pachon (2001) evaluated the diagnostic accuracy of 'Hoover's sign' in detecting COPD by assessing intra-observer agreement. One hundred and seventy two patients with a diagnosis of COPD were included in the study and attended a pulmonary outpatient clinic, where each patient was assessed for 'Hoover's sign' firstly by a junior medical doctor and then by a specialist pulmonologist. The results demonstrated that intra-observer agreement was 'high' between the two physicians (K statistic = 0.74), with Hoover's sign being more prevalent in patients with severe COPD. This suggests significant asynchrony needs to be present before Hoover's sign is visible. Therefore, while breathing asynchrony may exist, this abnormality appears to be associated with the severe stages of the disease pathway and may not be a useful indicator for monitoring chronic respiratory disease during the mild to moderate stages of the disease pathway.

2.2.4.3 Regional contributions of the ribcage and abdomen during tidal breathing

The movements induced by the chest during inspiration and expiration have generally been modelled as displacements arising from independent compartments of the ribcage and abdomen within the chest (Konno & Mead 1967) (section 2.3.5.1). Assessment of the regional contribution of each compartment during tidal breathing has had little application in the clinical setting, even though differences in the regional contribution of each

compartment to tidal breathing have been known to exist between health and respiratory disease (Aliverti et al. 2004; Dechman & Wilson 2004). In COPD, diminished abdominal movement during tidal breathing has been directly associated with diaphragmatic insufficiency secondary to hyperinflation (Cahalin et al. 2002; Ottenheijm et al. 2005). As a consequence these patients have been shown to have a characteristic 'apical' breathing pattern, which increases in the more severe stages of the disease pathway (Troyer & Estenne 1984). With increasing respiratory impairment and diaphragmatic insufficiency, accessory muscle recruitment has also been shown to increase, further distorting the balance between the contributions of ribcage and abdominal compartments (Orozco-Levi 2003).

In contrast, healthy adults have a greater percentage of their total motion related to their abdomen during tidal breathing (Romei et al. 2010). In physiotherapy practice, breathing retraining techniques have traditionally involved the teaching of diaphragmatic breathing to patients with COPD. One of the stated aims of the teaching is to optimise the diaphragmatic contribution during breathing to reduce symptoms such as increased work of breathing and breathlessness (Casciari et al. 1981; Dechman & Wilson 2004). However, to date, there is an absence of rigidly defined 'cut off' limits which define the normal range for each compartmental displacement. One of the reasons for this is because the quantitative measurement of the regional contributions of the ribcage and abdomen involves the use of laboratory based equipment, which is not well suited to the clinical environment. Therefore, even though known differences in the contributions of the ribcage and abdomen have been observed in health and disease (Gilmartin & Gibson 1984; Georgiadou et al. 2007), these parameters have yet to be considered in the monitoring of chronic respiratory disease because of the difficulties associated with objectively quantifying them.

2.2.4.4 Abnormalities in respiratory timing components

Respiratory rate

Respiratory rate is a broad indicator of respiratory stability and is easily obtained at the bedside (Tobin et al. 1983a). Regular documentation of respiratory rate has been used to assist in identifying patients at risk of serious adverse events such as cardiac arrest and admissions to Intensive Care Units (ICU) (Fieselmann et al. 1993; Hodgetts et al. 2002), as well as identifying the onset of COPD exacerbations (Yañez et al. 2012). In a prospective study, Yanez *et al* (2012) examined respiratory rate in 89 patients with a diagnosis of severe COPD, where each patient was monitored over a period of three months, or up until they had an exacerbation of COPD. Respiratory rate was monitored using a 'VisionOx' monitor that was installed into the home oxygen system of each patient. Mean respiratory rate was calculated during three different time periods each day over a period of three months, or until the patient had an acute exacerbation of COPD. However, the sampling period was not defined, and it was therefore not clear for how long respiratory rate was measured during each time period. The study reported that 30 of the 89 patients (33%) required hospitalisation following an exacerbation of COPD. Respiratory rate was shown to increase in the five days preceding an exacerbation of COPD in 21 of the 30 patients (70%), from 15.2 ± 4.3 /min to 19.1 ± 5.9 /min ($p < 0.05$) which was found to be statistically significant. No such significant increase was observed in the patients who did not have an exacerbation (16.1 ± 4.8 /min at the start of the study and 15.9 ± 4.9 /min at the end).

These findings highlight the clinical utility of quantifying specific elements of breathing pattern (such as respiratory rate) as a monitor of respiratory health. However, the examination of respiratory rate in isolation may have limited respiratory monitoring potential. Alterations in respiratory rate can accompany a variety of different respiratory and non-respiratory conditions, and respiratory rate is known to be associated with a number of behavioural and emotional factors (Boiten et al. 1994; Masaoka & Homma 1997).

Inspiration and expiration timings

Although respiratory rate is one of the most common parameters of breathing pattern that is routinely measured owing its ability to signify acute respiratory deterioration (Tobin et al. 1983b; Tobin et al. 1983a; Kennedy 2007; Yañez et al. 2012), the detailed examination of other elements of the respiratory cycle have yet to be translated into clinical practice. Information relating to respiratory timing components, such as inspiration and expiration timing (in seconds), has primarily been considered in the intensive care setting, during weaning from mechanical ventilation (Alia & Esteban 2000), or during laboratory based studies (Loveridge et al. 1986; Tobin 1992; Bruce 1996).

It is known that patients with COPD often have longer expiratory phases (Tobin et al. 1983b; Aliverti & Macklem 2001; Niewoehner 2010), which are attributed to airway obstruction making it more difficult to breathe out (GOLD 2014).

Although the extent of airways obstruction is traditionally assessed using spirometric lung function tests (such as FEV₁, % of predicted), the examination of expiration time during resting breathing has yet to be translated into clinical practice. Furthermore, unlike respiratory rate, there is an absence of rigidly defined normative cut off values for expiratory time. In an early study, Tobin (1983) recorded respiratory timing components in 47 younger adults (<50 years) and 18 older adults (>60 years) over a five minute period, where the average inspiratory time was reported to be 1.60 ± 0.30 and 1.67 ± 0.30 seconds respectively. These age-related differences may be too small to be of any clinical significance. In the same study, the average inspiration time in 11 patients with COPD was reported as 1.12 ± 0.25 seconds, in 15 patients with restrictive lung disease it was 0.96 ± 0.25 seconds and in 12 patients with pulmonary hypertension it was 0.96 ± 0.15 seconds (Tobin et al. 1983b). While it was not reported if any of these differences were statistically significant, these observations demonstrate that the analysis of respiratory timing components may be able to differentiate between health and disease. These parameters may therefore also be useful for detecting alterations in respiratory health. However at present, breathing pattern research has been restricted to the examination of single time point measurements of breathing pattern, so it is

uncertain if/how these parameters alter over time, with either disease progression or therapeutic intervention.

2.2.5 Summary of breathing pattern

This section has revealed that a number of respiratory diseases commonly present with abnormalities in the components of breathing pattern. However breathing pattern is an ill-defined area of research, partly because the term incorporates a number of respiratory parameters (Loveridge et al. 1986; Tobin 1992; Benchetrit 2000), and partly because most of these parameters lack any well-defined limits for normality. Amongst the respiratory parameters incorporated within breathing pattern, a decision was made to examine the following parameters in this research because of the information that they may provide about abnormalities in respiratory health:

- I. Respiratory timing parameters (inspiratory/expiratory time, breathing cycle time and respiratory rate)
- II. Regional contributions of the ribcage and abdomen during tidal breathing
- III. Relative volumes (inspiration and expiration magnitudes)

The next section will consider the most commonly used techniques for measuring breathing pattern.

2.3 Measurement of breathing pattern

Alterations in the parameters of breathing pattern have been associated with a number of respiratory abnormalities (Tobin et al. 1983b; Loveridge et al. 1986; Aliverti et al. 2004; Wijdicks 2007), however the practicalities associated with obtaining accurate measurements of breathing pattern have been challenging. The following section will examine some of the current methods available for measuring breathing pattern, and a rationale for selecting the measurement system used in this research will then be presented.

2.3.1 Clinical observation

Subjective observation of a number of breathing parameters can be performed easily at the bedside. An estimate of respiratory rate can be obtained by observing the number of times the chest expands within one minute, or more conveniently, by counting the number of breaths in 15 seconds and multiplying by four (Tobin 1992). While this method is relatively quick and easily performed, Tobin (1992) suggested that counting the number of breaths in a 15 second period and multiplying the by four, could induce error of up to four breaths per minute, particularly if a patient has an irregular breathing pattern. Although an error of four breaths per minute may not be important in healthy individuals, Tobin (1992) suggested that such error is a potentially dangerous if patients are respiratorily compromised, when the optimal range is narrower.

Unlike respiratory rate, absolute measurement of tidal volume cannot be made using visual inspection alone. However, clinicians routinely qualitatively assess tidal volume by visually evaluating whether a patient is taking 'deep' or 'shallow' breaths (Kennedy 2007). While this observational method is also quick and simple to perform, the subjective interpretation of relative tidal volume may vary between observers. Over estimation of tidal breathing could be particularly dangerous in patients with low tidal volumes (Tobin 1992).

Observing breathing asynchrony is performed by visually examining whether there is a paradoxical movement between the ribcage and abdomen during inspiration where the rib-cage displaces inwards during inspiration. While 'Hoover's sign' has been observed in patients with COPD (Hoover 1920), some evidence has suggested that there is a weak correlation between the detection of Hoover's sign and the presence of COPD (Godfrey et al. 1970). These conflicting reports indicate that observing chest wall for asynchrony is only of qualitative value, as the technique is highly subjective and the degree of breathing asynchrony can be variable between individuals.

In summary, visual inspection of breathing pattern is easy and quick to perform. However, the practice is subjective, which is dependent on the ability

of the observer to identify any abnormalities in the components of breathing pattern. Some of the most commonly used objective measurement systems for obtaining quantitative breathing pattern data will now be examined.

2.3.2 Pneumotachograph

Continuous monitoring of respiratory flow can be made using a pneumotachograph (PNT), which is considered as the gold standard for measuring tidal volume and flow in both the spontaneously breathing and ventilated patient (ATS 2003). The device works according to the assumption that the measurement of flow is directly proportional to the 'pressure gradient', which is generated by an individual breathing through a mouthpiece into a resistive element within the PNT (Kreit & Scirba 1996). Since flow is linearly related to the pressure gradient, this parameter can be converted to litres per second. The PNT is relatively easy to use in the ventilated patient by attaching the device to an endotracheal tube (a tube inserted into the trachea via the mouth or nose to maintain the patency of the airway) (Kreit & Scirba 1996).

In the spontaneously breathing patient, a mouthpiece or tightly fitted mask is required to cover the nose and mouth in order to ensure there is no air leakage through the mask. Loosely fitted masks can lead to air leaks. However one of the major limitations associated with the PNT is the invasive nature of face masks and mouth pieces. These have been poorly tolerated by critically ill patients and children. Their use requires patient co-operation, which can be challenging to obtain in these patient groups (Crenesse et al. 2001). Furthermore, the use of face masks and mouth pieces has been shown to cause instrument induced changes in breathing pattern (Askanazi et al. 1980; Perez & Tobin 1985).

2.3.3 Instrument induced changes in breathing pattern

Experimental studies have repeatedly shown that the use of face masks and mouthpieces employed within breathing pattern measurement systems (such as the PNT) have been associated with an increase in tidal volume (Gilbert et al.

1972; Askanazi et al. 1980; Perez & Tobin 1985), and a reduction in respiratory rate (Rodenstein & Mercenier 1980; Perez & Tobin 1985). These findings were reported when comparisons were made between breathing patterns obtained via a PNT and non-invasive measurements. The latter has typically been performed using Respiratory Inductive Plethysmography (RIP), which is a device that measures breathing patterns from the cross sectional changes of the rib cage and abdomen. RIP will be examined in more detail in section 2.3.5, but here the evidence supporting the theory that non-invasive measurement systems have little effect on breathing pattern in comparison to invasive techniques will now be critically reviewed.

In one of the earliest studies to document the influence of respiratory apparatus on breathing pattern, Gilbert *et al* (1972) measured breathing patterns from 14 healthy participants during two breathing conditions: 1) unrestrained breathing with magnetometers to measure the anterior-posterior displacements of the chest wall (Section 2.3.7) and 2) simultaneous recordings of breathing patterns with magnetometers and a spirometer, where participants breathed through a mouthpiece and were fitted with a nose clip. One of the major findings from the study was tidal volume increased in all but one participant (by an average of 123mls) during the second condition (with nose clips and mouthpieces), while respiratory rate was found to be consistently lower (mean=6bpm). However, it is not known if these differences were statistically significant as this early observational study did not perform statistical tests between the two conditions. Since this study was performed over four decades ago, respiratory magnetometers were used to measure breathing pattern non-invasively. Although respiratory magnetometers have been frequently used in the medical literature for estimating tidal volume (Tobin 1992; Banzett et al. 1995; Yan et al. 1996), one of the major concerns with their use is associated with their estimation of tidal volume from the anterior-posterior displacements of the chest (section 2.3.5.1). In reality, inspiration and expiration causes transverse expansion of the thorax as well as anterior-posterior movements (Konno & Mead 1967). These movements can be captured by other non-invasive respiratory monitoring systems (such as RIP),

which measure the circumferential displacement during tidal breathing, but not with magnetometers. Therefore, it is unclear whether the study by Gilbert *et al* (1972) captured the true breathing pattern during their measurements.

Despite these limitations, the finding that mouthpieces and nose clips are associated with an increase in tidal volume and a reduction in respiratory rate has been replicated in subsequent experimental studies which employed RIP as a non-invasive measure of breathing pattern (Perez & Tobin 1985; Rameckers *et al.* 2007). Perez and Tobin (1985) compared the breathing patterns produced from ten healthy participants during two different breathing conditions, namely 1) unrestrained breathing using RIP (with two bands positioned around the rib cage and abdomen), and 2) simultaneous recordings of breathing pattern with RIP and PNT. In line with previous findings by Gilbert *et al* (1972), when the respiratory route was altered (during the second condition), tidal volume was found to be significantly greater ($p < 0.001$) when compared to the first condition of unrestrained breathing. Respiratory rate was also found to be lower, although the differences did not reach statistical significance, possibly because the study was insufficiently powered ($n=10$). Although Perez and Tobin (1985) reportedly occluded nasal breathing, adhesive tape was used to make the seal instead of nose clips, which are traditionally used during measuring of volume involving PNT. These differences further highlight the methodological differences between studies examining the influence of respiratory apparatus on breathing pattern.

Askanazi *et al* (1980) examined breathing patterns measured from 28 healthy participants using a canopy spirometer system which consisted of a clear head chamber and neck seal to enable the monitoring of air flow and volume. Breathing patterns were recorded during four specific periods of interest: a) wearing a facemask b) using a mouthpiece c) wearing a nose clip and d) with no attachments at all. Results indicated that the use of a mouthpiece and nose clip caused an average increase of 32.5% and 15.5% in tidal volume respectively, when compared to breathing without any attachments. No change in respiratory rate was observed. However, one of the major criticisms of this study is concerned with the use of a 'canopy spirometer system', which is not

representative of the traditional methods used to measure volume and flow in clinical practice or laboratory based studies. These parameters are usually obtained using a PNT or spirometer (ATS 2003). Although spirometers and PNTs require facemasks and mouthpieces to obtain measurements of breathing pattern, they do not require the use of a head chamber. The use of a head chamber could feel restricting for participants, possibly causing an element of anxiety, which has been known to alter breathing pattern (Homma & Masaoka 2008). However, these limitations were not addressed in the study by Askanazi *et al* (1980).

It has become evident that studies investigating the influence of respiratory apparatus (namely mouth pieces and nose clips) on breathing pattern have varied substantially in the methods that they employed. However, despite these differences, their effect on increasing tidal volume has been a consistent finding, even though the influence on respiratory rate is less clear. This is possibly because of the differences between the methodologies used by these studies.

In summary, the PNT is considered to be the gold standard for the measurement of breathing parameters related to volume and flow (ATS 2003). In addition to the practical drawbacks associated with the placement of tightly fitted facemasks and mouth pieces, one of the major limitations of the technique relates to the change in breathing pattern induced by the face masks and mouth pieces (Gilbert *et al.* 1972; Askanazi *et al.* 1980; Perez & Tobin 1985). Examining breathing patterns obtained with external apparatus may therefore be an inaccurate representation of the complexities of natural breathing pattern. These observations highlight the importance of non-invasive respiratory monitoring systems for measuring breathing pattern. The following section will examine the available non-invasive monitors.

2.3.4 Non-invasive respiratory monitoring tools

To overcome the problems associated with instrument induced changes in breathing pattern caused by facemask and mouthpieces (Askanazi *et al.* 1980;

Perez & Tobin 1985), there has been considerable interest into the development of **non-invasive** respiratory monitoring systems over the past four decades.

The surface movement of the chest during tidal breathing has been used to extrapolate breathing pattern parameters relating to assumed volume, timing and relative contributions of the rib cage and abdomen (Konno & Mead 1967). A number of devices have been developed to capture the surface movement of the chest. The following section will review five of the most well recognised non-invasive technologies for obtaining breathing pattern from surface displacements of the chest, and a rationale for the selection of RIP, and the procedures used to calibrate RIP in this research will be provided at the end of this chapter.

2.3.4.1 Electrical Impedance Tomography

Electrical Impedance Tomography (EIT) is a non-invasive, radiation-free imaging technique used to estimate regional lung function and ventilation distribution through the production of images representing a cross sectional plane of the chest (Balleza et al. 2007; Balleza et al. 2010). Each image represents the distribution of electrical impedance across the chest according to the specific level that the electrodes are placed. Since the electrical conductivity of the lung is influenced by the air content, impedance in lung EIT is thought to be proportional to lung volume (Balleza et al. 2007; Leonhardt & Lachmann 2012). For example, an increase in lung volume (during inspiration) reduces the electrical impedance, while a reduction in lung volume (during expiration) increases the electrical impedance throughout the cross sectional plane of the chest.

EIT is operated by placing 16 electrodes around the circumference of the bare chest. These electrodes induce a high-frequency and low amplitude electrical current (100millivolts) to image the impedance changes. To generate the images, one pair of electrodes (called 'the driver pair'), send a weak electrical current through the chest to every remaining electrode pair. The remaining 13 pairs (called 'receiver pairs'), record the individual potential difference as a

voltage, depending on their location around the chest. Once a full circuit has been completed, the neighbouring pair of electrodes then acts as the ‘driver pair’. This process is completed 13 times, until every pair has recorded the potential difference (Figure 1) (Marquis et al. 2006; Leonhardt & Lachmann 2012).

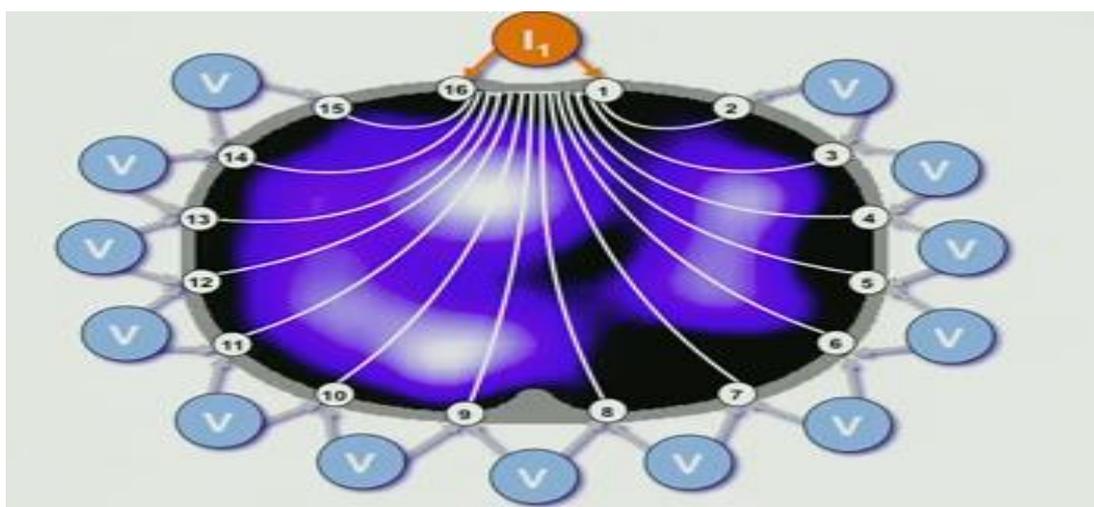


Figure 1. Schematic representation of a) the placement of the electrodes around the chest (numbered 1 to 16), and b) the impedance distribution over the cross sectional plane of the chest. A weak, electric current (I_1) is applied to the ‘driver electrodes’ (1 and 16), so that the remaining 13 ‘receiver pairs’ measure the potential difference as a voltage (V).

Once the internal impedance distribution has been calculated for every electrode pair, this voltage data set is used to reconstruct the conductivity profile so that images can be computed. Since changes in electrical impedance are thought to be linearly related to lung volume, relative lung volume can be calculated (Harris et al. 1987; Balleza et al. 2007). Generation of images from minimum impedance (during end-expiration) to maximum impedance (during end-inspiration) are subtracted to create a ‘tidal image’, which is the sum of relative volume changes during a tidal breath (Brown et al. 1985).

In respiratory monitoring, EIT has had some use within the acute intensive care setting to monitor regional lung function (Inéz 2000), although the majority of these studies have been conducted in the laboratory environment (Marquis et al. 2006; Balleza et al. 2007; Leonhardt & Lachmann 2012). Correlation

between changes in EIT images and global lung volume have been demonstrated in animal models (Adler et al. 1998), healthy adults (Brown et al. 1985; Harris et al. 1987; Balleza et al. 2007), and patients with respiratory disease (Balleza et al. 2010).

One of the most recent validation studies was performed by comparing measurements of tidal volume obtained from a 'new generation' EIT with direct measurements of tidal volume obtained using a gold standard PNT (Balleza et al. 2007). The new generation EIT claimed to save application time since the electrodes were already attached to the skin adhesives. Thirteen healthy adults aged between 20 and 55 years were fitted with a) EIT electrodes placed around the circumference of the thorax, and b) a PNT. Tidal volumes were simultaneously recorded by the two devices for a period of 30 seconds, where five to eight breaths were selected for the analysis. The study reported that mean tidal volume measured by the PNT and EIT was 0.52 ± 0.10 L and 0.53 ± 1.06 L respectively, where the difference was non-significant. Pearson's correlation coefficients showed excellent correlation between the two devices ($r^2 = 0.92$, $p = 0.001$), and Bland and Altman plots demonstrated excellent agreement between the two devices for measurements of tidal volume (mean of the differences = -0.003 L, 95% confidence interval -0.045 L to 0.038 L), suggesting that tidal volume could be measured interchangeably by the two devices. However, the findings from this study were based on the comparison of only five to eight breaths, which appeared to be selected randomly from the 30 second recording. Furthermore, the study reported an equipment failure rate of 10%, with artefacts caused by slippage of the electrodes, even though participants remained still throughout the recordings.

Since the electrical conductivity of blood and muscle is more effective than fat content, concerns regarding the influence of body shape on the quality of the measurement using EIT have also been raised (Marquis et al. 2006). However, one of the major reasons why EIT has yet to be adopted for frontline respiratory monitoring is because the device is not practical for the world outside the laboratory. EIT involves the placement of 16 electrodes placed around the chest, where each one needs to be connected to the proper cable.

Even for a well-trained practitioner this procedure can take up to 20 minutes to prepare (Balleza et al. 2007). From a research perspective, it is not yet known if a single cross sectional plane is representative of global ventilation.

2.3.4.2 Opto-Electronic Plethysmography

Opto-Electronic plethysmography (OEP) is a method used to estimate changes in lung volume by mapping the displacements of the chest wall using infrared cameras, and reflective surface markers placed around the torso (Aliverti & Pedotti 2002; Parreira et al. 2012; Layton et al. 2013). Chest wall mechanics and lung volume can be examined regionally according to a three compartmental model which incorporates; a) upper ribcage, b) lower ribcage and c) abdomen (Aliverti & Pedotti 2002; Parreira et al. 2012). One of the major stated advantages of OEP is that the tool can be used to obtain measurements of breathing pattern without a patient-specific calibration procedure, and breathing patterns can also be obtained during physical activity (Aliverti & Pedotti 2002).

To measure breathing pattern, an automatic analyser is used to detect the movement of 89 reflective markers placed around the chest wall, which includes 37 anterior markers, 42 posterior and 10 laterally. The anatomical positions of these markers are arranged between the sternal notch, and the clavicle, then to the level of the superior iliac crest.

The three-dimensional coordinates of each reflective marker can be tracked using a minimum of four cameras positioned in the space around the participant. Each camera simultaneously projects a beam of infrared light at the same time as recording. The beam of infrared light emitted by each camera flash is reflected by the markers and recorded by the camera with a maximal sampling rate of 120Hz. The signal from each camera is then computed simultaneously so that the three-dimensional X-Y-Z coordinates can be reconstructed using complex algorithms.

Experimental validation studies have demonstrated that OEP has a good linear relationship with simultaneous measurements of tidal volume obtained using a

spirometer or PNT (Cala et al. 1996; Aliverti et al. 2000; Aliverti et al. 2004; Layton et al. 2013). In one of the most recently published validation studies, Layton et al (2013) compared measurements of tidal volume obtained from OEP and a spirometer during a maximal exercise cycling test. Thirty two healthy participants between the ages of 18 and 40 years performed a single graded exercise test on a cycle ergometer while simultaneous measurements of lung volume were obtained using spirometry and OEP. After a five minute resting period, a three minute warm up (submaximal) exercise was performed on the ergometer with no resistance. This was followed by a further three minute period described as 'maximal' exercise, where participants were asked to cycle with an increased resistive load so that they achieved 'maximal aerobic capacity'. This was defined as heart rate more than 90% of the predicted maximum, and it was reported that all participants met this criterion. Lung volumes from the first three minutes of 'submaximal' exercise, and the last three minutes of 'maximal' exercise were analysed. It was reported that 'equal numbers of breaths' were taken from the OEP data, however there was no clear indication of how these breaths were selected, or how many breaths were selected throughout the three minute recording. Overall, the mean difference between tidal volume measured with spirometry and OEP during submaximal and maximal exercise $0.054 \pm 0.04\text{L}$ and $0.086 \pm 0.05\text{L}$ respectively. This equated to a discrepancy of 2.0% during submaximal and 3.9% during maximal exercise, which was not statistically significant. Similar discrepancies have previously been reported when comparing OEP and spirometry at rest, as differences between measurements of tidal volume have been reported to be between 1.7% and 3.4% (Cala et al. 1996; Aliverti et al. 2000). In the study by Layton *et al* (2013), there was a strong correlation between measurements of tidal volume obtained using OEP and spirometry submaximal exercise ($r = 0.963$, $p < 0.001$), and at maximal exercise ($r = 0.982$, $p < 0.001$). Bland and Altman limits of agreement demonstrated that tidal volume measured by OEP at submaximal exercise may be 0.13L above or -0.025L below spirometry, and at maximal exercise 0.188L above or 0.017L below spirometry, suggesting that the two devices can be used interchangeably to measure volume.

Despite the reported accuracy of OEP in obtaining changes in tidal volume, this technology is also confined to a laboratory setting because there is a need for significant financial outlay and the set-up is very complex. In addition to requiring the placement of 89 reflective markers around the bare torso (which could have limited patient acceptability), four standing cameras need to be positioned around the periphery. This requires a designated operational space and the system cannot be easily transported.

2.3.4.3 Structured Light Plethysmography

In the past five years, Structured Light Plethysmography (SLP) has emerged as an entirely contactless technology for monitoring lung function, the components of breathing pattern, and chest wall mechanics. The system is based on similar principles to OEP in that it uses computer image technology to estimate the parameters of breathing patterns from the movement of the chest wall (Chen et al. 2010; Alimohamed et al. 2011). However, unlike OEP, SLP is quicker and simpler to perform and is better adapted to the clinical environment in terms of its design. SLP works by projecting a grid pattern onto the anterior chest, either in a seated, standing or sitting position. Participants are required to wear a tightly fitted white t-shirt, and the measurement is ideally performed within a darkened room so that the grid can be clearly projected on to the anterior chest wall surface. The position of the grid is determined according to the location of the sternum. Two digital cameras are used to 'track' the dynamic 3D position of the grid 'intersection points' induced during inspiration and expiration. These are defined as a corner that is shared by four squares. Based on the movement of the grid intersection points induced during inspiration and expiration, a 3D image of the chest wall can be reconstructed using complex algorithms (Chen et al. 2010).

The advantage of SLP is that the technology can be used to measure excursions of the chest wall according to right and left sides, as well as ribcage and abdomen. Each quadrant can be separately analysed so that breathing patterns can be compared between regions. From a practical perspective, the raw data files can be rapidly analysed and downloaded into a spreadsheet

format. However information regarding the reconstruction algorithms have not been made available by the developers. It is therefore unclear as to how the breathing pattern data is extrapolated from the raw data file.

Even though the concept of SLP has been around for the past three decades, the device has only become commercially available in the past five years (Chen et al. 2010). As a consequence, independent information regarding the validity and reliability of the system currently remains limited. Validation studies are only available in the form of conference abstracts, and have been funded by the developers (Alimohamed et al. 2011). So far, these preliminary studies have suggested good validity against the gold standard PNT in healthy adults in terms of inspiration time. In a recently published conference abstract, Alimohamed *et al* (2011) examined the validity of SLP against a PNT in terms of reproducibility and repeatability, as well as the influence of body position. SLP and PNT were simultaneously used to measure breathing patterns from 10 'randomly chosen' adults (ages were not stated), although it is not clear how long each recording period lasted. Reproducibility was examined by recording breathing patterns by three different operators, while repeatability was examined by collecting data from one participant and then another data set 40 minutes after the initial one. Only one breathing parameter was extracted (inspiration time (sec)) and paired t tests revealed that the differences between mean inspiration time obtained by the two devices were not statistically significant. However, paired t tests are an inappropriate tool for method comparison studies because they do not examine the agreement between the two devices (Bland 1986). Comparisons of inspiration time obtained by three different operators found no significant differences between the recordings; (1 vs 2, $p = 0.73$; 1 vs 3, $p = 0.97$; 2 vs 3, $p = 0.73$) or between two different body positions (sitting and lying). It was therefore concluded that SLP is not time, operator or position dependant. (Alimohamed et al. 2011). However, the analysis was limited to the examination of mean inspiration time, and therefore the positive conclusions of the investigation cannot be assumed for other breathing parameters. Furthermore, comparing the SLP to the PNT is not a direct like-for-like comparison, as the two technologies are designed to

measure different things. A more logical comparison would be between the SLP and RIP as both measure chest wall excursion, but this has yet to be carried out. These findings highlight that while SLP has been appropriately designed for clinical use, there is a need for peer-reviewed research that validates the device independently to determine its accuracy in obtaining measurements of breathing patterns

Another concern regarding SLP relates to the location where the breathing pattern data are acquired. While every non-invasive monitoring system extrapolates breathing patterns from the cross sectional movements of the chest wall, SLP obtains data exclusively from the anterior excursions of the chest, and not the lateral or posterior excursion. Examining the possibility of extrapolating breathing patterns from anterior excursions of the chest wall as a surrogate for circumferential measurements needs further evaluation. Finally, the system requires patients to wear a tightly fitted white t-shirt. This may affect patient acceptability as patients with respiratory diseases may find this difficult to put on and restricting to movement. Patients also need to remain completely still throughout the recording period. Any additional movement can distort the tracking of the grid intersection points, causing artefacts in the data.

For all the above reasons, SLP is not yet recommended for clinical use, nor was it appropriate for the research in this thesis.

2.3.5 Respiratory magnetometers and Respiratory Inductive Plethysmography

OEP uses a three-compartment model of respiration, but other devices (respiratory magnetometers and Respiratory Inductive Plethysmography (RIP)) have used a two-compartment model. These latter devices measure breathing pattern from the cross sectional changes in the rib cage and abdomen during inspiration and expiration. The next section will examine the theory underpinning the estimation of tidal volume from the movements of the rib cage and abdomen. The use of respiratory magnetometers and RIP for

measuring cross sectional area changes will be examined due to their widespread documented use, and procedures used for calibrating RIP will also be presented. Finally, a justification for the selection of RIP and the procedure used to calibrate the breathing pattern data in the current research will be discussed.

2.3.5.1 The Konno and Mead Model (1967)

Konno and Mead (1967) proposed that the volume of air moving in and out of the lungs could be deduced from chest wall movements (Konno & Mead 1967). Movements of the chest wall are caused by respiratory muscle activity in response to changes in intra-thoracic pressure which results in inspiration and expiration. To produce inspiration, contraction of the diaphragm moves the abdomen forward and downwards, increasing the vertical dimensions of the thorax (Romei et al. 2010). The rib cage, which is attached to the external intercostal muscles, is also lifted outwards and forwards during inspiration, increasing the diameter of the thorax both laterally, and anteroposteriorly. Movement of the chest wall during expiration is a passive process. To permit expiration, the diaphragm and intercostal muscles relax so that the chest wall returns to the position it adopts for resting volume (Romei et al. 2010; Kaneko & Horie 2012).

Under the Konno and Mead model (1967), the chest was described as having two anatomical subdivisions; the rib cage (RC) and abdomen (AB), where the dividing surface between them was said to be the diaphragm. Anatomically, each 'compartment' incorporates parts of the body outside the lungs which share changes in lung volume during inspiration and expiration. Konno and Mead (1967) highlighted that while the two compartments could move as a single unit during tidal breathing, the two parts could also move independently. For example, it is possible inspire predominantly from the abdomen, or the ribcage. Inward displacement of one compartment, while the other compartment is displaced outward can also be achieved. In light of these observations, the Konno and Mead model was based on the following assumptions;

1. The chest moves with two degrees of freedom, from the rib cage and the abdomen during inspiration and expiration.
2. Each degree of freedom corresponds to the radial expansion of a given compartment.

Based on these assumptions, Konno and Mead (1967) developed the following hypotheses:

1. Changes in volume can be deduced from the changes in cross sectional area of each of the two compartments (ie, the RC and AB).
2. Changes in volume in each individual compartment (RC and AB) can be summed to estimate tidal volume:

$$V_T = \Delta V_{RC} + \Delta V_{AB} \quad (1)$$

In formula 1, V_T refers to tidal volume, where ΔV_{RC} and ΔV_{AB} are the changes in the volume of the rib cage and abdomen respectively. This is the formula for estimating tidal volume using RIP that is presented in most published papers (Loudon et al. 1988; Tobin 1992; Lee et al. 1993; Winkworth et al. 1994). It is implicit in the application of this model to RIP measurements that any change in volume can be estimated from changes in the cross sectional area of each compartment, where the height of each compartment is assumed to be fixed.

Any device that measures the changes in the cross sectional area of the rib cage and abdomen during inspiration and expiration could therefore theoretically be used to calculate tidal volume (discussed later in this chapter). However, in order to derive absolute tidal volume from the cross sectional area change, direct calibration is needed. For example, this can be achieved by simultaneously measuring tidal volume from the device that measures rib cage and abdominal excursions (like RIP), and a PNT, and using regression methods. Any change in tidal volume measured using a PNT is assumed to be linearly related to the radial expansion of each compartment. However, this calibration process can be time consuming, and the use of face masks and mouthpieces are poorly tolerated by children and critically ill patients (Crenesse et al. 2001). Furthermore, if a PNT is able to be used, the additional advantage of using RIP

in parallel is not clear. As a consequence, techniques used for measuring lung volume based on the Konno and Mead model have frequently concentrated on *relative* changes in tidal volume (Chadha et al. 1982; Sackner et al. 1989; Banzett et al. 1995; De Groot et al. 2001). These changes can be measured with simpler calibration processes than those used to measure absolute tidal volume. The available RIP calibration methods will be discussed later in this chapter (section 2.3.9).

2.3.5.2 Limitations of the Konno and Mead model

To date, a small number of devices have been developed which have been based on the Konno and Mead model (section 2.3.7), and this method of estimating tidal volume has been used extensively in the literature (Chadha et al. 1982; Loudon et al. 1988; Lee et al. 1993; Fiamma et al. 2007). However, the majority of these studies have accepted all the assumptions of the Konno and Mead model without any consideration for the potential flaws, and the impact that these may have on their measurements. An important point in the model is the assumption of two degrees of freedom. In reality the chest wall moves with four degrees of freedom, these are the expansions of the rib cage and abdomen (radially), and the change in the height of each of the compartments (vertically) (Tobin et al. 1983c). The change in the height of the chest was not considered in the Konno and Mead model, instead the heights of each compartment were assumed to be fixed. The assumption that the height of each compartment is fixed becomes less convincing if posture changes during measurement. In sitting, moving to a 'slumped' posture can reduce the height of the compartments, while sitting upright increases the vertical dimensions of each compartment. These factors need careful consideration in studies measuring breathing patterns while in sitting, as subconscious changes in sitting posture throughout the recording period can potentially violate the assumptions of the Konno and Mead model. However, studies incorporating RIP to measure breathing pattern in a sitting position have not indicated whether the sitting position of participants were monitored or controlled (Loudon et al. 1988; Lee et al. 1993; Winkworth et al. 1995; Brown et al. 1998).

A limitation of any method that measures changes in rib cage and abdominal displacements to estimate tidal volume is that the overall changes in lung volume incorporate not only changes in air volume (induced during inspiration and expiration), but also changes in blood volume that shifts in and out of the chest cavity. Therefore, the measurement of chest wall displacements as a surrogate for measuring tidal volume directly could also be influenced by blood shifting in the chest cavity. This can occur when the lungs are subject to large pressure changes, such as extreme changes in posture. While this may not pose a problem in studies examining breathing patterns during a single posture, such as sitting, such influence should be considered during studies that involve changes in posture, such as during sleep studies.

While these issues highlight some of the drawbacks associated with the Konno and Mead model for estimating tidal volume from the displacements of the individual rib cage and abdominal compartments, it is generally agreed that a better model has yet to be proposed. The next section will examine the devices available for measuring breathing pattern according to the Konno and Mead model.

2.3.6 Devices based on the Konno and Mead Model

Two devices, namely **respiratory magnetometers** and **Respiratory Inductive Plethysmography (RIP)**, have been extensively used in the literature for estimating changes in tidal volume (based on the Konno and Mead model). The major difference between these two devices is concerned with the way in which the cross sectional area of the ribcage and abdominal compartment are measured. While respiratory magnetometers assume that the change in the cross sectional area is concentrated in the anterior-posterior motion of the anterior chest, RIP measures the cross sectional changes from the circumferential change in each compartment. Other devices have also been developed to measure changes in cross sectional area, such pneumobelts, however these devices are no longer commercially available. Therefore, the two main devices available for measuring rib cage and abdominal motion, respiratory magnetometers and RIP, will now be discussed.

2.3.7 Respiratory magnetometers

Respiratory magnetometers measure the displacement of the rib cage and abdominal compartments during tidal breathing. They consist of pairs of electromagnetic coils which are placed parallel to each other around the circumference of the rib cage and abdominal compartments of the chest (Konno & Mead 1967). Within each pair, one coil acts as the transducer, transmitting a high frequency electromagnetic field to the 'receiver coil'. To measure the changes in the antero-posterior diameter of the ribcage during tidal breathing, one coil is placed over the sternum at the level of the fourth intercostal space, and the other is placed over the spine at the same level. For measuring changes in the antero-posterior diameter of the abdomen, another pair of magnetometer coils are placed one on the abdomen at the level of the umbilicus, and the other over the spine at the same level. As the rib cage and abdomen displace inwards and outwards during tidal breathing, the distance between the anterior and posterior coils at the level of the rib cage and abdomen increases (during and inspiration) and decreases (during expiration). During this process, the output voltage is linearly related to the distance between the pair of coils. However, this is only applies if each pair of magnetometers remain on the same parallel axis (Banzett et al. 1995).

Displacement of the coils, caused by slippage or rotation of the trunk, can alter the voltage induced between the transducer and receiver coil. Therefore, the magnetometer must be well secured around the bare chest, and trunk rotation minimised. One limitation concerns the influence of surrounding metal structures and electric devices. These devices project additional electromagnetic fields which can interfere with the electromagnetic field produced by the magnetometers, and as a consequence, this can interfere with the magnetometer output voltage.

While this interference may be easily manipulated in a laboratory setting, these drawbacks highlight the reasons why magnetometers have generally been confined to the laboratory environment. However, the major drawback of respiratory magnetometers concerns their measurement of antero-posterior

changes of the rib cage and abdominal compartments. In reality, the chest wall displaces transversely, as well as antero-posteriorly. Therefore, respiratory magnetometers may be insensitive to lateral motion of the chest.

2.3.8 Respiratory Inductive Plethysmography (RIP)

Respiratory Inductive Plethysmography (RIP) is the gold standard non-invasive method for quantifying ventilation and the components of breathing pattern from the cross sectional changes in the rib cage and abdominal compartments (Chadha et al. 1982; Tobin et al. 1983c; Adams et al. 1993b; Carry et al. 1997). The advantage of this system over respiratory magnetometers is that it measures the cross sectional changes inclusive of transverse changes, as well as anterior-posterior changes. RIP can be used in the presence of other electronic devices, as the chosen frequency of the inductance does not interfere with other medical equipment. Unlike EIT and OEP, RIP is portable and only requires the placement of two elasticated bands around the circumference of the rib cage and abdomen.

To date, RIP has had a wide application in a number of different populations and settings. RIP was first used for estimating tidal volume in healthy adults at rest (Tobin et al. 1983a; Brullmann et al. 2010), and during exercise and sleep within the laboratory environment (Cantineau et al. 1992; Caretti et al. 1994). However, soon the application of RIP was extended to patient populations, such as patients with COPD and asthma (Tobin et al. 1983b; Brack et al. 2007; Frisk et al. 2014), and the technology has also had applications within the intensive care environment in anaesthetised and ventilated patients (Valta et al. 1992).

RIP uses two sensor bands placed around the rib cage and abdomen (figure 2). The two bands consist of a Teflon insulated wire sewn in a 'zig zag' pattern, embedded within the elastic belts. The elastic property of the bands enables them to stretch and shrink during cross sectional changes induced by inspiration and expiration. The wires from each band are connected to an oscillator module that produces a weak sinusoidal current of approximately 20

millivolts at 300 kHz. When the alternating current is passed through the bands, a weak electromagnetic field is created around the circumference of the ribcage and abdomen. As the chest wall displaces inwards and outwards during inspiration and expiration, an opposing current is created for each compartment which is measured as a change in voltage. The changes can then be captured and stored on a computer to allow a breath-by-breath analysis, where signals can be calibrated to estimate breathing parameters relating to volume (section 2.3.9).

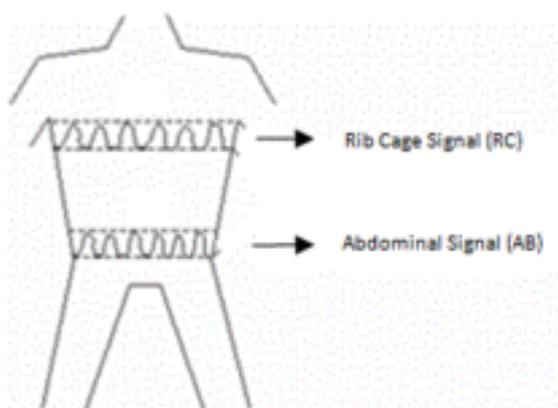


Figure 2 Anatomical placement of the RIP bands for the rib cage (RC) and abdominal (AB) compartments

2.3.9 Calibration of Respiratory Inductive Plethysmography

Introduction to calibration

Calibration of RIP is the process of determining the mapping between displacement of the chest wall and inhaled (or exhaled) air volume (tidal breathing). In parallel with the development of RIP, several attempts have been made to define calibration procedures to estimate volume changes from chest wall movements induced during inspiration and expiration (Chadha et al. 1982; Sackner et al. 1989; Banzett et al. 1995). Without a calibration procedure, RIP can show qualitative (Poole et al. 2000) and relative changes in breathing

parameters. The latter can be quantified, but cannot provide absolute estimates of tidal volume. This section will examine some of the most commonly used procedures for calibrating RIP.

Theoretical principles underpinning RIP calibration procedures

Calibration of RIP is based on the Konno and Mead model, which assumes that the chest cavity is divided into two anatomical subdivisions, namely the ribcage and the abdominal compartments, separated by the diaphragm. A detailed explanation of this model can be found in section 2.3.5.1.

Tidal volume can be estimated using formula 2:

$$V_T = \Delta V_{RC} + \Delta V_{AB} \quad (2)$$

On the assumption that the change in tidal volume is linearly related to the changes in the cross sectional area of each compartment, formula 2 can be rewritten as:

$$V_T = M(K(\Delta uV_{RC}) + \Delta uV_{AB}) \quad (3)$$

In formula 3, V_T is the tidal volume, ΔuV_{RC} and ΔuV_{AB} are the changes in the uncalibrated rib cage and abdominal volumes measured by the RIP signal, and K and M are the constants to be determined by calibration (Sackner et al. 1989). Here, 'K' is a constant of proportionality which accounts for the differences in the heights of compartments, and M scales the RIP output to be equivalent to tidal volume as measured by a PNT. If only K is determined and M is assumed to be $M=1$, then relative calibration can be obtained. The need to determine K is concerned with the anatomical height of the rib cage and abdominal compartments, as the height of the rib cage is approximately twice the height of the abdomen. This means that unit expansion in the rib cage is associated with a larger volume increase than unit expansion in the abdomen. K scales the equation to take account of this difference in height.

The following sections will now examine the most commonly used methods for calibrating RIP; 1) Isovolumetric manoeuvre, 2) Qualitative Diagnostic Calibration, and 3) Fixed calibration.

2.3.9.1 Isovolume manoeuvre

Konno and Mead (1967) described the technique for obtaining the volume-motion coefficients for the rib cage and abdominal compartments. Firstly, the relative gains of the RIP are adjusted so that the amplitude of the ribcage and abdominal signal were equal. Secondly, participants were asked to breathe in a known volume of air measured by a PNT. The nose and mouth were then occluded, and participants were asked to shift the known volume of air between the rib cage and abdominal compartments using coordinated contractions of the diaphragm and inspiratory intercostal muscles. Each cycle took between five and ten second to perform, and the expansion/contraction of the rib cage and abdomen was recorded assuming that a fixed volume of air was moving back and forth between each compartment. With the mouth closed, the 'system' was described as having one degree of freedom because the volume inside the 'closed system' was constant. Therefore, a change in volume in one compartment was equal and opposite to the volume change in the other. However, to be of any value, the Isovolume manoeuvre needs to be performed correctly. One of the main reasons why this technique has been regarded unfavourably is because of the difficulty in performing the manoeuvre. The technique requires active participation, and needs to be taught correctly. Konno and Mead (1967) reported that while some participants were able to perform the manoeuvre on their first attempt, others were only able to do this 'after a little practice', although the actual number of attempts was not defined. Furthermore, the demographics of these participants were not reported. This technique would have limited compliance in a range of populations including children, critically ill patients, individuals with cognitive or communicative impairments, or even healthy participants. Finally, since the technique relies on the use of an external PNT, this adds to the complexity of the measurement and means it would have limited acceptability in a Primary Care setting, because of space and time constraints associated with its use.

2.3.9.2 Statistical methods for calibrating RIP

As a way of improving the practicality of calibrating RIP, statistical methods were later developed to estimate the constant, K (Banzett et al. 1995). These can be supplemented by estimating M (the factor that scales the output of the RIP output to be equivalent to absolute tidal volume), however this usually involves the use of a PNT.

A number of methods have been proposed for estimating K. In the following sections, Qualitative Diagnostic Calibration (QDC), and the Fixed calibration procedure will be discussed due to their extensive use in existing studies using RIP for finding 'K' (Banzett et al. 1995; Sackner 1996; De Groote et al. 2001). Justification for the calibration procedures used in this investigation will then be presented at the end of this section.

2.3.9.3 Qualitative Diagnostic Calibration (QDC)

Qualitative Diagnostic Calibration (QDC) (Sacker *et al* 1989) was proposed as an alternative method for calibrating RIP without the need for using the isovolume manoeuvre. The advantages of this method are that 1) QDC can be performed during periods of 'natural' breathing, without the need for measuring the change in volume directly (Barbousa et al. 2012), and 2) the computerised procedure can be performed retrospectively, reducing the complexity of the procedure used to record breathing pattern. The QDC method is based on the same assumptions as those outlined by Konno and Mead (1967) (see section 2.3.5.1), as well as two additional assumptions;

1. The statistical selection of breaths from a five minute calibration period is assumed to provide a set of breaths with constant tidal volume, but with different rib cage and abdominal contributions.
2. There is intrinsic variability in the relative contributions of the rib cage and abdomen to tidal breathing.

Using the Konno and Mead model (1967), Sacker *et al* (1989) expressed the relative change in volume measured at the mouth (V_T) as the sum of the

change in volume from the rib cage (ΔV_{RC}) and change in volume from the abdominal (ΔV_{AB}) compartment (formula 4);

$$V_T = K\Delta uV_{RC} + \Delta uV_{AB} \quad (4)$$

Instead of using the isovolume manoeuvre to produce zero change in V_T to calculate K, Sackner *et al* (1989) proposed that the collection of breaths over a five minute period, with the exclusion of any large or small breaths (for example greater than ± 1 SD of the mean breath size), might approximate a constant tidal volume (formula 5);

$$SD(V_T) = SD(K\Delta uV_{RC} + \Delta uV_{AB}) \quad (5)$$

It was assumed that:

1. ΔuV_{RC} and ΔuV_{AB} are independent
2. The standard deviation of V_T is equal to zero, because breaths that differed by more than one standard deviation were excluded from the analysis.

Therefore, formula 5 can be re-written as the following equation (6):

$$K*SD(\Delta uV_{RC}) + SD(\Delta uV_{AB}) = 0 \quad (6)$$

K could then be solved for using the following equation (7):

$$K = -SD(\Delta uV_{AB})/SD(\Delta uV_{RC}) \quad (7)$$

To date, a number of studies have calibrated RIP using the QDC technique (Adams et al. 1993a; Poole et al. 2000; Groote et al. 2002). Although the procedure benefits from being simple to perform, one of the weaknesses of the QDC method relates to the retrospective selection of breaths that are within one standard deviation from the mean breath size. The removal of 'large' and 'small' breaths is based on a fairly arbitrary criterion for size. Additionally, the five minute calibration period that is obtained prior to the recording period may not be representative of natural breathing pattern with respect to the variability in contribution of RC and AB. It may be possible that participants are anxious at the beginning of the recording period because they

are in unfamiliar laboratory surroundings. However, it is not possible to limit these influences, and a number of studies have recorded resting breathing pattern using RIP calibrated by QDC. Despite the theoretical limitations of the QDC procedure, there is evidence to suggest that there is good agreement between measurements of tidal volume obtained using this method and a gold standard in children (Sackner 1996; Brown et al. 1998), and adults (Sackner 1996; De Groot et al. 2001).

In a previous validation study by Sackner *et al* (1989), values of K, which were derived using QDC and isovolume manoeuvre, were compared during a five minute period of tidal breathing and simulated Cheyne-Stokes breathing in ten healthy adults (Sackner et al. 1989). The major finding from the study was that no statistically significant differences between the mean of the tidal volume obtained using QDC and isovolume manoeuvre were observed. Five minutes of regular breathing and Cheyne-Stroke breathing had mean deviations of $3.4\% \pm 1.6$ and $4.9\% \pm 3.1$ respectively between the two methods. Furthermore, there was no significant difference between tidal volumes obtained by RIP calibrated using the QDC protocol and PNT. However, despite these non-significant findings, comparing the methods based on their mean differences is not sufficient for demonstrating the validity of the procedure. Other qualities of the procedure, such as the agreement, were not assessed. Therefore, while this method may not be superior to other calibration methods that are based on statistical estimation (such as fixed calibration, which is discussed next), these findings seem to suggest that QDC may be at least as good as other methods to adjust the electrical gain for rib cage and abdomen for tidal volume estimation during quiet breathing and Cheyne-Stokes breathing in a single posture.

2.3.9.4 Fixed calibration

A fixed calibration procedure was proposed by Banzett *et al* (1995) as a method to minimise the error associated with statistical estimation of K. Fixed calibration assumes that K remains similar across a wide range of breathing styles, and therefore uses a 'pre-set' K factor to weight the RC and AB gains

during every recording period. Banzett *et al* (1995) suggested that the error in tidal volume calculation may remain similar over a wide range of K factors. The stated advantages of this method were that the technique is simple to perform and possibly reduces the statistical error associated with the QDC method of calibration (Poole et al. 2000). Banzett *et al* (1995) proposed the use of a fixed ratio of 2:1 (ribcage-to-abdomen), which was justified on the basis that anatomically, the volume of the rib cage is larger than the volume of the abdomen, so a motion of a given size of its surface produces a greater lung volume change than an equal motion of the abdomen. Therefore, the rib cage motion signal is provided with a larger gain. It was hypothesised that the rib cage is twice as long in a vertical direction compared to the abdomen in ‘most people’, during seated tidal breathing.

Fixed calibration was validated in six healthy male (aged between 22 and 46 years), and five healthy female (23 and 31 years) participants. While it was stated that the participants were chosen to provide a range of normal body types, these were not detailed. Displacements of the rib cage and abdominal compartments were measured using RIP, while changes in actual volume were obtained simultaneously using a spirometer. Calibration was achieved using equation 8, which was previously described in section 2.3.9:

$$V_T = K\Delta V_{RC} + \Delta V_{AB} \quad (8)$$

Based on the anatomy of the chest wall, a range of fixed values were chosen to represent the RC and AB standard gain ratio K (8, 4, 2 and 1). Measurements of tidal volume from the RIP based on this method of calibration were then compared to the absolute tidal volume obtained using the spirometer in terms of ‘mean absolute error’. Results showed that using a standard ratio during quiet breathing, the mean error of tidal volume was approximately 35ml which equates to 1 to 8% of spirometric tidal volume. However, infrequent errors approaching 100% were observed. During mixed breathing the errors were larger than normal breathing but the median error remained less than 100ml. The error was generally less than 10% of the spirometric tidal volume. In general, the larger errors were found during dis-coordinated breathing,

suggesting this method should be used with caution in individuals who have an abnormal or dis-coordinated breathing pattern, such as patients with chronic respiratory disease (Tobin et al. 1983b; Poole et al. 2000).

2.3.10 Validation of Respiratory Inductive Plethysmography

To date, a number of published studies have examined the validity of RIP, where calibration plays a major role in the evaluation of its accuracy. Validity refers to whether a measure actually measures what it is meant to measure (Guyatt et al. 1993). Various concepts have been used to define validity. Some of these include; content validity (the extent to which a measure represents all aspects of a given social situation) (Fitzpatrick 1983); Face validity (the extent to which a measure measures what is intended) (Broder et al. 2007); Construct validity (the degree to which a measure measures what it claims) (Cronbach & Meehl 1955) and criterion validity (ability of the outcome measure to measure accurately) (Guyatt et al. 1993). The latter is usually achieved by comparing the measure against a gold standard.

In the case of RIP, most studies examining the validity of the device have compared the data measured against a PNT (Chadha & Sackner 1983; Tobin et al. 1983c). This is fine for validating respiratory rate but is possibly not the most useful comparator for many other aspects of breathing pattern, such as the regional contributions of the rib cage and abdomen. Evaluation of the validity of RIP is a complex matter because breathing patterns are known to be influenced by a number of internal and external factors (Fiamma et al. 2007; Homma & Masaoka 2008). Where internal factors include features such as the presence of respiratory disease and age, external factors refer to the influence of sleep, and activity, such as rest and exercise. The validity of RIP has therefore been examined in a number of different populations and conditions including; in healthy adults (Carry et al. 1997; Fiamma et al. 2007) patients with chronic respiratory diseases (such as COPD, acute respiratory failure and restrictive lung disease) (Tobin et al. 1983c), children (Revow et al. 1987; Brown et al. 1998) as well as during different conditions, such as during sleep,

at rest, during exercise and in different positions (such as sitting and lying) (Cantineau et al. 1992; Caretti et al. 1994).

Since the current investigation is concerned with the examination of breathing and speech breathing patterns in healthy adults and participants with chronic respiratory disease, the next section will therefore focus on the validation of RIP exclusively in these participant populations

2.3.10.1 Validation of Respiratory Inductive Plethysmography in healthy adults

In healthy adults, the agreement between RIP and PNT has been examined for various parameters of breathing pattern including tidal volume, inspiration time, expiration time, breathing cycle time (Carry et al. 1997; Fiamma et al. 2007). Agreement between the two devices has been found to be 'good' to 'excellent' in healthy adults (Fiamma et al. 2007). The influence of body position throughout the recording period has not been shown to have a significant effect on the validity of the device, as no significant differences have been found in the validity of breathing patterns obtained during a sitting, lying or standing position (Brullmann et al. 2010). From a methodological point of view, studies examining the validity of RIP can be criticised for; a) having a small sample size (ranging between 8 and 20 participants), b) examining short extracts of data (ranging from as little as 6 breaths to 10 minute recording), c) distracting participants with music during the recordings, d) analysing mean differences and not agreement. However, despite these drawbacks, the literature examining the validity of RIP generally report that the device can be used interchangeably with a PNT in healthy adults at rest, irrespective of their body position.

In one of the most recent validation studies, Fiamma *et al* (2007) compared breathing patterns obtained simultaneously between RIP and a PNT. Eight healthy adults were examined (six males; mean age 26.5 ± 2 years) during a single recording session. Participants were firstly attached to a PNT via a mouthpiece, and a nose clip was used to prevent any air from escaping. Participants were then set up with the RIP, which involved connection to the

device via two bands that were placed circumferentially around the rib cage and abdominal compartments. Simultaneous measurements of tidal volume using a PNT and RIP were obtained during a ten minute quiet breathing period, where each participant was asked to sit in a chair and listen to music that was 'emotionally and rhythmically neutral'. The rationale for using music was to distract the participants' attention away from their breathing. However, the influence of music has been shown to be an independent factor for altering breathing pattern (Homma & Masaoka 2008). The correlation between PNT and RIP was assessed for tidal volume, and it was found to be significant ($p < 0.05$), the agreement between PNT and RIP measurements was further assessed using the graphical analysis of Bland and Altman (1986).

During simultaneous recordings of breathing pattern using the PNT and RIP, the mean values of tidal volume, inspiration time, expiration time and breathing cycle time were significantly correlated for each parameter (r values always above 0.75, with p always below 0.03). Bland and Altman plots demonstrated good agreement between the two devices for each breathing parameter as all data points remained closely bound around the horizontal 'mean of the differences' line, with no evidence of bias, and within limits of agreement that were not clinically relevant. It was therefore concluded that the RIP and PNT could be used interchangeably to measure breathing pattern. Although this study was based on a very small sample ($n=8$), one of the advantages of the analysis was that the findings were based on the examination of a 10 minute recording period. Traditionally, the majority of studies investigating the validation of the RIP have based their findings on the analysis of a 'cluster of breaths', sometimes as few as six breaths (Tobin 1992). Since breathing patterns have been associated with variability over time (Benchetrit et al. 1989), the examination of six breaths may not be an accurate representation of the actual breathing pattern, especially when participants are undergoing simultaneous recordings of breathing pattern using a PNT, as the use of a PNT has been associated with decreased breathing variability (Wysocki et al. 2006). The process of extracting the 'cluster of breaths' from breathing pattern recordings can be seen as a further limitation as studies often do not

justify the selection process. This could increase the possibility of introducing an element of researcher bias into the measurement.

Although studies examining the validity of RIP in healthy adults at rest have reported that the device can be used interchangeably with the gold standard PNT (Carry et al. 1997; Fiamma et al. 2007), RIP appears to become less accurate when recording breathing patterns during periods of exercise. Caretti *et al* (1994) compared measurements of tidal volume simultaneously obtained from a flow meter and RIP during an incremental treadmill and cycling exercise. Eight healthy adults participated in the study, and they were each asked to cycle (on the static bike) and walk (on the treadmill) at incremented levels of intensity: 60watts (w), 90w, 120w, 150w and 180w. Participants remained at each speed for a period of two minutes and breathing patterns were recorded with the RIP and PNT during the tasks. The study concluded that RIP could be used to measure breathing patterns in healthy adults during periods of exercise. However, closer examination of the findings does not appear to support this conclusion. This is because the study reported that when the intensity was below 150w, 63% of participants did not differ significantly between the two devices. When the intensity increased to 180w significant differences between the two devices were found for 50% (four) of the participants. Although the agreement between the two devices was not assessed, these findings suggest that the accuracy of RIP reduces as the intensity of the exercise increased.

These findings are similar to those published by Sackner *et al* (1890) who also validated RIP against a spirometer in six young adults during periods of moderate exercise on a treadmill. While the study concluded RIP appears to be a useful monitor of breathing pattern during periods of exercise, the results indicated that tidal volumes deviated as much as $\pm 20\%$ from the actual spirometric volume obtained by the PNT.

From a practical perspective, the accuracy of the RIP can be influenced by slippage of the RIP bands during movement. This suggests that traditional RIP may not be suitable for the measurement of breathing patterns during periods

of exercise (Caretto et al. 1994), because the bands appear to respond to positional changes, as well as changes in the anterior-posterior motions of the chest wall during tidal breathing.

2.3.10.2 Validation of Respiratory Inductive Plethysmography in patients with respiratory disease

The majority of the experimental validation studies have been conducted in healthy adults; fewer studies have evaluated the validity of the tool in patients with chronic respiratory disease. In one study, validation of RIP was examined in patients with COPD (n=21), restrictive lung disease (n=9) and acute respiratory failure (n=19) who required assisted ventilation (Tobin et al. 1983c) RIP was validated against a PNT during normal breathing in sitting and supine postures in ambulatory patients, while patients with acute respiratory failure were only examined in supine. Validation of the device was based on the comparison of a 20 second recording period simultaneously obtained from the PNT and RIP, where it was reported that each 20 second recording produced six breaths on average. Measurements of tidal volume obtained using the two devices were compared by calculating the percentage deviation from the PNT. This was calculated as $\frac{RIP - PNT}{PNT} \times 100\%$. Deviations of $\pm 10\%$ were considered as clinically acceptable. In patients with COPD, 69% of breaths across all participants were within $\pm 5\%$ of the actual spirometric value, while 100% of the group remained within $\pm 10\%$. No value deviated by more than 10% in either the sitting or supine position. In patients with restrictive lung disease, the mean deviation in the sitting and supine position was $\pm 2.5\%$ and $\pm 5.8\%$ respectively. In the 19 patients with respiratory failure requiring assisted ventilation, the study reported that there was a 3.9% deviation from the spirometric value, however a deviation of 11 % was noted in two participants. Although this study was limited by a) the analysis of only six breathing cycles and b) looking at the percentage deviation without considering the agreement between the two devices, these findings suggest that RIP is valid in patients with chronic respiratory disease who are considered as 'stable'. However, the device should be used with caution in patients with acute respiratory failure requiring assisted ventilation. One of the reasons why breathing pattern

measurements obtained using RIP cannot be equated exactly to spirometry could be because there is a difference in the volumes being compared. Where the PNT indirectly derives volume from a pressure drop measured at the mouth, RIP derives the displacement of the thoracic volume from the change in the area enclosed by the bands. It is possible that displacements of the chest wall could also be influenced by shifts of non-gaseous volumes, such as blood.

In summary, RIP has been reported to be valid in the recording of breathing patterns from both healthy adults and adults with stable chronic respiratory disease at rest. The latter data have been drawn primarily from patients with COPD, and little is yet known about the validity of RIP in other respiratory diseases.

2.4 Rationale for the selection of Respiratory Inductive Plethysmography in the current research

It is evident from the literature that each breathing pattern measurement system (including RIP) is associated with a number of limitations relating to practicality, validity, and reliability; so the decision to use RIP was based the following reasoning process.

Firstly, it was deemed desirable to use a non-invasive system to minimise the problems of instrument induced changes in breathing pattern (Askanazi et al. 1980; Perez & Tobin 1985). As a consequence, the PNT was ruled out because it required the use of face masks and out pieces. Secondly, the parameters of interest were respiratory timings and relative contributions of the parts of the chest wall, each of which can be assessed adequately by non-invasive means. Of the non-invasive choices, RIP has significant practical advantages over OEP and EIT in that the system simply requires the placement of ribcage and abdominal bands to obtain breathing pattern (Konno & Mead 1967). In contrast, the arrangement of 89 reflective markers used for OEP (Aliverti et al. 2000) and 16 circumferential electrodes used for EIT (Marquis et al. 2006; Balleza et al. 2007), have largely restricted these measurement systems to the specialist laboratory environments because of the time and space required to

operate the systems. In particular, OEP also requires extensive clinical space for the arrangement of four cameras around the participant, which means the device cannot be easily stored or moved. While the majority of studies that have employed RIP have also been conducted within the laboratory environment (Tobin et al. 1983c; Caretti et al. 1994; Fiamma et al. 2007), RIP has more portability and requires limited space to store the device.

SLP offers an alternative to the RIP but is currently too novel to have been properly evaluated. In contrast, RIP has been extensively and independently validated in healthy adults, patients with chronic respiratory disease (Tobin et al. 1983c), children (Warren & Alderson 1985), and well as in the supine and sitting positions (Chadha & Sackner 1983). RIP is therefore considered to be the gold standard for the non-invasive measurement of breathing pattern and was the technology of choice for this research.

2.4.1 Justification for the selection of a procedure for calibrating Respiratory Inductive Plethysmography

Following the decision to use RIP in the current research, there was a need to select a calibration procedure so that breathing patterns measured by the RIP could be quantified. Section 2.3.9 evaluated the methods available for calibrating RIP, where the limitations associated with each method were highlighted. As no calibration procedure is without flaws, the decision to use the QDC procedure in the current research was based on a compromise between its acknowledged limitations, and pragmatic factors such as participant acceptability. The reasoning process was as follows:

The isovolume manoeuvre was firstly excluded from further consideration because of the practical challenges associated with performing the procedure. Irrespective of disease status, age or mental ability, teaching any participant to occlude the nose and mouth, then shift a known volume of air back and forth between the rib cage and abdomen using co-ordinated contractions of the diaphragm and intercostal muscles is difficult. Poorly performed Isovolume manoeuvres can lead to erroneous gain ratios, and inaccurate estimations of

tidal volumes. Therefore, statistical methods for calibrating RIP (such as the QDC and fixed calibration) were considered to have a major advantage over the isovolume manoeuvre because these procedures are not reliant on subject participation.

From a pragmatic perspective, a further decision was made to perform relative calibration in order to exclude the need for a PNT. Performing relative calibration means that estimations are proportional to tidal volume, but calibrated in absolute units such as millilitres (ml). This is because neither the QDC procedure nor fixed calibration method derive 'M' (the absolute measure of tidal volume obtained using the PNT). Not only have face masks and mouth pieces been shown to cause instrument induced changes in breathing pattern, the use of a PNT would increase the need for additional clinical space, and would add to the complexity of the measurement. If breathing/speech breathing patterns are to be used as a future respiratory monitoring tool, simplifying the system for obtaining them would be advantageous.

Having made the decision to use relative calibration, it was decided that deriving M (which scales the RIP output to be equivalent to tidal volume measured by a PNT), was not required, because the researcher was mainly interested in examining respiratory timing components and the regional contributions of the rib cage and abdomen. Obtaining absolute estimations of tidal volume using statistical methods is not possible.

Of the statistical methods that have been frequently used in the literature for calibrating RIP, fixed calibration was considered unfavourably because of the errors (>100ml) that have been observed during periods of discoordinated breathing (Banzett et al. 1995). Discoordinated breathing patterns are a common feature in patients with chronic disease including asthma, COPD and bronchiectasis (Gilmartin & Gibson 1984; Garcia-Pachon 2002). Since people with these conditions were included in the current research, potential errors of more than 100ml were deemed as unacceptable. Furthermore, fixed calibration has not been widely used to calibrate RIP, so there is limited available data even in healthy populations.

While the drawbacks of QDC have been acknowledged, this procedure is the most widely used statistical method for calibrating RIP, where the validity of the procedure has been demonstrated during periods of natural breathing, as well as during simulated Cheyne-Stokes breathing. QDC was selected as the calibration method of choice in the current research. All data (healthy young, healthy old, self-reported asthma, and patients with COPD and bronchiectasis) were calibrated using the same procedure in attempt to remove calibration as a confounder during the comparative analysis.

2.5 Summary of chapter two

It has been revealed that the methods currently used for monitoring respiratory health in Primary Care are associated with a number of drawbacks related to practicalities of obtaining the measure, and the information that they provide. Since a number of respiratory diseases commonly present with abnormal breathing patterns relating to respiratory timings, volumes and the regional contributions of the ribcage and abdomen, the detection/measurement of these abnormalities might serve as a useful tool for monitoring changes in respiratory health. A number of techniques and devices are available for monitoring breathing pattern, but the drawbacks identified with subjective observation and methods which require the use of face masks and mouthpieces (such as the PNT), have highlighted the importance of selecting a tool which is both objective, and non-invasive. OEP, EIT and SLP each obtain quantitative measurements of breathing patterns from the surface movements of the chest; however, OEP and EIT require specialist laboratory environments. SLP has not yet been sufficiently evaluated to allow it to be recommended. In contrast, RIP has demonstrated superiority over all these devices in terms of practicality combined with good validity. RIP is the current gold standard method for the non-invasive measurement of breathing pattern, and has therefore been selected as the measurement system of choice in this research.

Chapter Three

The burden of chronic respiratory disease

The care of patients with chronic respiratory disease imposes one of the biggest diagnostic and therapeutic challenges for health care systems worldwide (Pauwels et al. 2001; Hawkins et al. 2013), as chronic respiratory diseases have been projected to become the third leading cause of mortality by 2020 (Cruz 2007; Rabe et al. 2007). Asthma, bronchiectasis and COPD are conditions which are considered under the umbrella of chronic respiratory disease, however the definition also extends to respiratory cancers and fibrosis (BTS 2006).

Central to the definition of chronic respiratory disease is its tendency to be of slow progression and long duration. Many of these diseases have been associated with a number of systemic complications. (Garcia-Aymerich et al. 2003; Agustí 2007; Wedzicha & Seemungal 2007). In addition to the primary disability imposed by respiratory deterioration (breathlessness), patients with chronic respiratory disease can also be limited by secondary extrapulmonary effects, such as reduced functional exercise capacity, which is particularly associated with the later stages of the disease (Gross 2001; Watz et al. 2008). As a consequence, the care of patients with chronic respiratory disease involves lifelong medical attention, as therapeutic goals centre on symptom management and enhancement of quality of life, rather than cure (Rabe et al. 2007). Symptom management also relates to the treatment of sporadic exacerbations (periodic episodes of acute respiratory deterioration) (Donaldson & Wedzicha 2006). In the case of COPD for example, acute exacerbations of the disease accounts for one of the major causes of emergency hospital admissions in the UK. These have risen steadily since the 1990s (Garcia-Aymerich et al. 2003; Connolly et al. 2006; Donaldson & Wedzicha 2006). While the definition of an acute exacerbation of COPD lacks universal consensus, it is generally agreed that the most distinct symptoms are increased breathlessness and sputum volume, although patients may also experience a decline in their physical capacity as a secondary complication

(Donaldson & Wedzicha 2006). According to epidemiological studies, the frequency of exacerbations has been estimated to be between 2.5 and 3 per patient, per year (Donaldson & Wedzicha 2006). Furthermore, exacerbations are associated with impaired quality of life (Seemungal et al. 2000), reduced survival (Soler-Cataluña et al. 2005) and patients are prone to re-admission to hospital (Garcia-Aymerich et al. 2003).

The value of detecting early changes in respiratory health is becoming increasingly recognised, as early treatment of exacerbations has been shown to reduce hospitalisations and enhance clinical recovery (Wilkinson et al. 2004; Soler-Cataluña et al. 2005; Connolly et al. 2006). Not all episodes of respiratory exacerbations lead to hospital admission (Donaldson & Wedzicha 2006). Some cases can be prevented by the Primary Care service (Morgan 2003), suggesting the importance of the early detection of respiratory decline. Finding an acceptable method to monitor changes in respiratory health remains a challenge, as a number of limitations have been associated with the current methods used to monitor respiratory health in the primary care setting.

This thesis is primarily concerned with the examination of the breathing patterns produced during speech (speech breathing patterns – see chapter five), as a potential marker of respiratory health. The studies have involved healthy adults, adults with a self-reported history of asthma, diagnosed patients with COPD and diagnosed patients with bronchiectasis. The next section will therefore describe asthma, COPD and bronchiectasis in more detail.

3.1 Asthma

Asthma is a common condition which affects 5 million children and adults in the UK and costs the NHS in excess of £1 billion (European Respiratory Society 2015). The disease often develops from childhood, however, people of all ages can develop the condition (BTS 2014). The fundamental causes of asthma are not fully understood. Genetic predisposition in combination with exposure to airborne allergens are believed to be the major cause, although environmental

triggers, such as cold air, extreme emotional arousal and some medication (such as aspirin and beta-blockers) have also been shown to contribute to the inflammatory response (Sykes & Johnston 2008; John Henderson 2013).

Asthma is a chronic inflammatory disease associated with variable and partially reversible airflow obstruction, which is characterised by recurrent episodes of breathlessness, wheezing, chest tightness and coughing, of varying intensity and frequency (Chung et al. 2014; NICE 2015). The condition is considered to be heterogeneous with a natural history of acute exacerbations (attacks), on a background of chronic airways inflammation, which is consistent with reduced lung function. Episodes of exacerbations can vary in intensity and frequency. These can be life threatening if left untreated because of asphyxiation caused by severe bronchorestriction, which can occur during an attack (John Henderson 2013).

3.1.1 Pathophysiology of asthma

Despite the widespread prevalence of asthma, the pathophysiology of the condition still remains poorly understood. Asthma is a complex, heterogeneous disease, where multiple pathways are thought to contribute to the development of the condition (Holgate 2008). To discuss every pathway is beyond the scope of this Thesis, however in broad terms, the pathophysiology of asthma has been categorised according to two processes, namely inflammation of the airways and hyper-responsiveness. These will now be described.

Airways inflammation in asthma is a multicellular process involving the infiltration of inflammatory cells such as neutrophils, eosinophils, CD4+T Lymphocytes and mast cells, and inflammatory mediators such as cytokines, which amplify the inflammatory response. Infiltration of eosinophil (which are a type of white blood cell) have been shown to be a major feature of the condition (Holgate 2008). Increases in eosinophils have been shown to significantly correlate with asthma severity (Fahy 2009; Katz et al. 2014), and a number of studies have demonstrated that treatment with corticosteroids reduces the eosinophils, resulting in symptomatic improvement (Fukakusa et

al. 2005). The inflammatory process predominantly involves the large airways, although, with increasing disease severity, the inflammation spreads distally to the small airways (Kraft et al. 1999; Holgate 2008). However, despite the identification of the inflammatory factors responsible for the pathophysiology of asthma, how the inflammatory process is initiated is an ongoing area of enquiry. Genetics, sex, environmental factors and respiratory infections are believed to contribute to the pathogenesis, although the exact mechanisms are not yet fully understood (Elias et al. 2003).

Airways hyperresponsiveness has been considered to be one hallmark of asthma, where bronchial provocation tests have been useful for assessing the presence of hyperresponsiveness and have aided in the diagnosis of the condition (Brannan & Loughheed 2012). Airways inflammation is one contributor to airway hyper-responsiveness, and has been defined as an exaggerated bronchoconstrictor response to a wide range of stimuli. However, the feature is not necessarily unique to asthma (Brusasco et al. 1998).

3.1.2 Diagnosis of asthma

There is currently no definitive diagnostic test for asthma, and the definition of the type, severity or frequency of symptoms has yet to be standardised. Unlike COPD, The absence of a gold standard definition means that it is not possible to make clear evidence based recommendations on how to make a diagnosis. One of the challenges associated with diagnosing asthma is related to its tendency to remit and relapse. Symptoms of asthma can also be generic, resulting in diagnostic confusion with other chronic disease which share a similar clinical presentation, such as COPD (section 3.2) (BTS 2014).

In light of these challenges, a diagnosis of asthma in adults is currently based on the combined findings from symptom questionnaires, response to anti-inflammatory medications and bronchodilators, and assessments of lung function airways hyper-responsiveness (during Methacholine challenge testing) (BTS 2014). While the symptomatic profile of asthma is similar to other chronic respiratory disease (such as breathlessness, wheezing and chest tightness), the

conditions under which they occur can help to inform the diagnosis. For example: Following exposure to cold air and allergens, after exercise, and during respiratory infections. A history of these conditional symptoms increases the diagnostic probability of having the disease (NICE 2015).

In the presence of clinically relevant signs and symptoms, recent clinical guidelines advocate the use of spirometry as the first line investigation for asthma (NICE 2015). When performed correctly, lung function testing can provide rapid information about the extent of airflow obstruction (Miller et al. 2005). The ratio of Forced Expiratory Volume in one second (FEV_1) to Forced Vital Capacity (FVC) (FEV_1/FVC ratio) is considered positive for airways obstruction if $<70\%$ (NICE 2015). However, lung function testing has limited application when considered in isolation because severe airflow obstruction can be present in the absence of any clinically relevant signs and symptoms. Peak Expiratory Flow (PEF) variability is usually monitored for a period of 2-4 weeks if there is diagnostic uncertainty after the initial assessment (Quackenboss et al. 1991). Current clinical guidelines recognise a positive test PEF variability as $>20\%$ (NICE 2015). This is calculated as the difference between the highest and lowest PEF expressed as a percentage of the mean. However, this test has been reported to be more useful for monitoring patients with established asthma, rather than making an initial diagnosis (BTS 2014).

A number of tests have been used to assess the likelihood of asthma. Methacholine challenge testing is considered when more conservative methods have failed to either eliminate or confirm the diagnosis, such as measuring lung function before and after bronchodilators (NICE 2015). Since airways hyper-responsiveness is one of the major characteristics of asthma, Methacholine challenge testing is a method of testing the extent of the hyper-responsiveness. When inhaled, Methacholine is an agent which provokes the airways to contract involuntarily, and narrow in the presence of asthma. However, normal results do not necessarily exclude a diagnosis of asthma, while abnormal findings are not always definitive. Furthermore, these tests have been largely used in research and specialist units, as they have not yet

widely accessible in everyday clinical practice (Brannan & Loughheed 2012; Chung et al. 2014).

While evidence based guidelines have provided a stepwise approach to aid in the diagnosis of asthma, it has become evident that the diagnosis of the condition is challenging because of the absence of a gold standard test, which can potentially lead to delayed and sub-optimal treatment.

3.1.3 Management of asthma

Evidence-based recommendations for the management of asthma have been broadly categorised into 1) supported self-management, 2) pharmacological management and 3) non-pharmacological management (BTS 2014).

Self-management is focused on the medical aspects of managing a variable condition on a day to day basis. Systematic reviews have repeatedly shown that self-management education which incorporates personalised asthma action plans (PAAPs) significantly improves a number of patient centred end points in patients with asthma (Gibson 2003; Bussey-Smith & Rossen 2007). In these reviews, successful programmes varied considerably, however the core components included patient education and personalised asthma action plans, where current guidelines advocate that these should be supported by regular professional review (BTS 2014).

Pharmacotherapy management of asthma involves a step-wise approach to minimise symptoms and optimise peak flow. Asthma medication is broadly categorised into short-acting inhaled beta agonists (reliever medications) and inhaled corticosteroids (BTS 2014). Although pharmacotherapy for asthma is effective and can provide control for many patients (Bateman et al. 2008), surveys repeatedly show that outcomes remain sub-optimal (Demoly et al. 2012). Many patients have concerns about taking regular medication, particularly inhaled corticosteroids. Up to 79% of adults and 78% of children report use of complementary and alternative medicine for their asthma (Slader et al. 2006). Breathing techniques are amongst the most commonly used complementary techniques, with up to 30% of asthma patients reporting

having used them to control symptoms (Ernst 2000). Although many clinicians remain sceptical, there is now a convincing body of evidence that breathing training for people with asthma is effective in improving patient-reported endpoints such as symptoms, health status and psychological well-being, and may be effective in reducing rescue bronchodilator medication usage (Thomas et al. 2003; Bruton & Holgate 2005; Burgess et al. 2011).

3.2 Chronic Obstructive Pulmonary Disease (COPD)

Chronic Obstructive Pulmonary Disease (COPD) is the term used to describe a group of progressive respiratory diseases, which are characterised by chronic airflow limitation that is not fully reversible (WHO 2011). Progressive expiratory flow limitation is the hallmark of COPD, however the disease is multidimensional, with various clinical manifestations (NICE 2010; GOLD 2014). Physiological impairments can be localised (within the lungs), or systemic (Petty 2003; Halbert et al. 2006). COPD is the fourth leading cause of mortality worldwide and its prevalence has been projected to increase even though COPD is both a preventable and treatable condition (WHO 2004; GOLD 2014). Prevalence data estimates that there are 900,000 people who currently have COPD in the UK (WHO 2004), however this figure is thought to be largely underestimated because COPD is a poorly diagnosed condition, especially in the early stages of the disease pathway (Spruit & Singh 2013; GOLD 2014). Patients with COPD have been shown to be largely asymptomatic in the earlier stages (Takahashi et al. 2003; Rabe et al. 2007; Bednarek et al. 2008), and lung function tests have been shown to highlight changes only once considerable damage to the airway has already occurred (Rabe et al. 2007; BTS 2013).

3.2.1 Pathophysiology of COPD

The current hypothesis for the pathogenesis for COPD is that the disease is caused by an 'abnormal' inflammatory response to the inhalation of toxic particles and gasses (MacNee 2005; Rabe et al. 2007; Forey et al. 2011; GOLD 2014). Inhalation of tobacco smoke has been recognised as the primary risk

factor for developing COPD (Fletcher & Peto 1977; Forey et al. 2011; GOLD 2014), which accounts for up to 80% of all reported cases. However, COPD affects only 15-25% of all smokers (MacNee 2005; Roth 2008). Although all individuals who smoke demonstrate signs of progressive lung inflammation, the vast majority of this population do not go on to develop COPD (Teramoto 2007; Yoshida & Tuder 2007; Forey et al. 2011), suggesting an inherent predisposition to developing the disease. Injury to the lung epithelium has been shown to be directly proportional to the concentration or dose of tobacco smoke exposure over time (Yoshida & Tuder 2007; Forey et al. 2011). Several factors can influence the exposure to cigarette smoke including; a) the type of tobacco smoked; b) the concentration of tobacco (*ie*, whether the tobacco has been mixed with other materials; c) the quantity, d) the depth of each breath and e) the frequency of inhalation (Dijkstra et al. 2014). A number of epidemiological studies have also implicated the role of increases in atmospheric sulphur dioxide (SO₂) and nitrogen dioxide (NO₂) in developing COPD (Andersen et al. 2011; Atkinson et al. 2014). However, unlike tobacco smoke inhalation, there is insufficient evidence to suggest a causal relationship (Ko & Hui 2012; Atkinson et al. 2014).

The abnormal inflammatory response to noxious agents has yet to be fully characterised, and it is possible that there are multiple pathways leading to the pathogenesis of COPD, which is beyond the scope of this thesis. In addition to the enhanced inflammatory response to inhaled cigarette smoke, two other processes are involved in the pathogenesis of COPD, namely imbalances between proteases and antiproteases and an imbalance between oxidants and antioxidants (oxidative stress). However, the majority of individuals go on to develop the disease following an abnormal inflammatory response to repeated tobacco smoke exposure.

Although there is evidence of lung inflammation in all individuals who smoke, there appears to be an enhanced inflammatory response to inhaled noxious agents which is beyond the normal inflammatory response in individuals who go on to develop COPD (Saetta 1999; Yoshida & Tuder 2007; Roth 2008). Most notably, bronchial biopsies from patients with COPD show a marked increase

in inflammatory cell infiltration compared to smokers who have not developed the disease (Di Stefano et al. 2004); the examination of bronchial mucosa in patients with COPD show an increase in T lymphocytes, neutrophils (Di Stefano et al. 1998); and there is a 5-10 fold increase in the number of macrophages in the airways and lung parenchyma of patients who have COPD compared to smokers who do not have the disease (Keatings et al. 1996). These release pro-inflammatory mediators have the potential to secrete proteinases, including neutrophil 'elastase', which reduces alveolar wall integrity and contributes to the emphysematous changes seen in COPD. A cycle of repeated inflammation is sustained because the pro-inflammatory factors released by the activated immune cells stimulate the production and secretion of additional pro-inflammatory factors, thereby encouraging more neutrophils and macrophages to the previously inflamed site (Nicod 2005; Tzortzaki & Siafakas 2009). The intensity of the inflammation appears to correlate with the degree of COPD progression (Rabe et al. 2007; Forey et al. 2011), and the inflammation can be exacerbated further in the presence of bacterial or viral infection, resulting in an acute-on-chronic inflammation (MacNee 2005; Yoshida & Tudor 2007).

The amplified inflammatory response to repeated cigarette exposure results in a number of structural changes, namely alveolar wall destruction (emphysema) and mucociliary dysfunction, which is responsible for impaired mucus clearance (Halbert et al. 2006; Rabe et al. 2007). These structural abnormalities lead to the characteristic narrowing of the airways seen in patients with COPD, and ultimately contribute to expiratory flow limitation, which has been used to define the disease (GOLD 2014). While age plays a significant role in lung function decline, adults who smoke demonstrate an accelerated rate of decline in FEV₁ (approximately 50mL per year), compared to those who have never smoked (approximately 38mL per year) (Fletcher & Peto 1977; Lalley 2013). This has been shown to occur in a dose dependant relationship with cigarette exposure (Forey et al. 2011).

3.2.2 Diagnosis of COPD

A diagnosis of COPD is considered in the presence of clinically relevant signs and symptoms, and reduced performance in objective lung function tests. Progressive expiratory flow limitation is the hallmark of COPD, and a diagnosis of COPD is considered if post bronchodilator Forced Expiratory Volume in one second (FEV_1) is less than 80% of the predicted value for age and sex (GOLD 2014). In an attempt to categorise the severity of the heterogeneous disease, the Global Initiative for Obstructive Lung Disease (GOLD) has provided a progressive 'staging' system with clear cut-off points, based on post bronchodilator FEV_1 ratio to Forced Vital Capacity (FVC). These stages range from 'mild' airway limitation to 'very severe' using the following spirometric criteria; Gold stage 1 (mild); $FEV_1/FVC < 0.7$ or $FEV_1 > 80\%$ predicted, Gold stage 2 (moderate); $FEV_1/FVC < 0.7$ or $FEV_1 < 79\%$ predicted, GOLD stage 3 (severe) $FEV_1/FVC < 0.7$ and $FEV_1 < 49\%$ predicted, and Gold stage 4 (very severe); $FEV_1/FVC < 0.7$ and $FEV_1 < 30\%$ predicted (GOLD 2014). So far this grading system has been shown to be a useful predictor of mortality, where the higher GOLD stages have been associated with greater mortality (Donaldson & Wedzicha 2006; GOLD 2014). The criteria have also been used to inform clinical decision making and to guide treatment, as a number of management strategies (such as Pulmonary Rehabilitation) are offered to patients based on the severity of airflow limitation (NICE 2010).

Although a diagnosis of COPD cannot be confirmed in the absence of spirometry, the use of post-bronchodilator FEV_1 has had limited application when considered in isolation. Spirometry cannot separate COPD from asthma (Takahashi et al. 2003), and correlates poorly with clinically relevant signs and symptoms such as breathlessness, exercise intolerance and quality of life (Ketelaars et al. 1996; Zielinski & Bednarek 2001). Therefore, current evidence based guidelines advocate that post-bronchodilator lung function tests should be used to confirm a diagnosis in the presence of other clinically relevant signs and symptoms in adults who are over the age of 35 (NICE 2010; GOLD 2014). These include; progressive external dyspnoea (graded using the Medical Research Council (MRC) dyspnoea scale), chronic cough (either productive or

unproductive), chronic sputum production, variable wheezing, chest tightness and frequent 'winter' bronchitis. Other signs such as hyperinflated and barrel shaped chest, blood gas imbalances, peripheral oedema, cyanosis, use of accessory muscles, pursed lip breathing and peripheral muscle imbalances have also used to inform the clinical picture (Gross 2001; Halbert et al. 2006; Rabe et al. 2007). However, these impairments have generally been associated with the more advanced stages of the disease process.

Despite the clear spirometric criteria set out by GOLD (2014) for diagnosing COPD, COPD remains a largely underdiagnosed and misdiagnosed condition. The symptomatic profile of patients with COPD is heterogeneous. A number of studies have shown that patients with early signs of the disease tend to under report their symptoms (Bellia et al. 2003; Takahashi et al. 2003). This is partly because symptoms can appear minimal in the early stages, or perceived to be part of the normal aging process (Buffels et al. 2004). Under-diagnosis of COPD may also be related to diagnostic confusion with asthma (Dodge et al. 1986). Asthma and COPD share a number of clinical similarities, the two conditions can co-exist simultaneously, given the high prevalence of asthma in patients who have COPD (Silva et al. 2004). Due to the barriers associated with the diagnosis of COPD, the majority of patients who make up the COPD population are considered as being in the moderate stages of the disease pathway (GOLD 2014).

3.2.3 Management of COPD

There is a strong consensus amongst evidence based clinical guidelines that the management of COPD should firstly encourage smoking cessation at every available opportunity, regardless of smoking status (Rabe et al. 2007; NICE 2010; GOLD 2014). Longitudinal studies have repeatedly shown that individuals who successfully stop smoking both slow down the decline in FEV₁ and delay their mortality (Fletcher & Peto 1977; Pride 2001; Tønnesen 2013). However, airways inflammation persists even after the smoking has stopped and the precise mechanisms for the persistence after the stimulus has been removed remains to be identified (Hogg 2006).

Up to date clinical guidelines have recommend a multidimensional, stepwise approach for the management of COPD which a) reduces the risk factors, b) monitors the progression, c) manage stable COPD and d) manage exacerbations (NICE 2010; GOLD 2014). While existing pharmacotherapies have yet to stop the progression of airways inflammation, bronchodilators are routinely used in the management COPD. These are provided on an 'as needed' basis to inhibit bronchoconstriction (NICE 2010; Ejiófor & Turner 2013; GOLD 2014). The main bronchodilators currently prescribed for patients with symptomatic COPD are beta-agonists (relievers which relax the muscles surrounding the small airways) and anticholinergics (which block the action of the neurotransmitter acetylcholine). A combination of these therapies may also be used (NICE 2010). However, while the development of COPD is based on an inflammatory pathway, the effects of anti-inflammatory bronchodilators have been disappointing. Inhaled corticosteroids are the most potent form of anti-inflammatories available, however trials have failed to show a consistent effect of these medications in the rate of FEV₁ decline (Burge 2000; Price et al. 2013). Systematic treatment with corticosteroids has been advised to be avoided because of the unfavourable benefit-to-risk ratio (NICE 2010; Price et al. 2013).

The management of COPD is therefore based on preventative and rehabilitative goals rather than cure, as COPD is a progressive disease (GOLD 2014). A significant proportion of the management strategy for patients with COPD has been based on the non-pharmacological management of the secondary (systemic) complications, where Pulmonary Rehabilitation (see chapter 4) has played a significant role in the management of patients who are considered as medically stable (BTS 2013; Spruit & Singh 2013).

3.3 Bronchiectasis

Bronchiectasis is a chronic respiratory disease which is characterised by irreversible dilatation and thickening of part of the bronchial tree (localised), or throughout the lung (diffuse) (O'Donnell 2008). Involved bronchi are dilated, inflamed and easily collapsible resulting in airflow obstruction and impaired clearance of thick viscous airways secretions, (Barker 2002; Hacken N 2010;

Pasteur & Hill 2010). There is a general belief that the incidence has been falling over the past 50 years because of the introduction of antibiotics and improved awareness about the underlying pathophysiology (Pasteur et al. 2000; Barker 2002; O'Donnell 2008; Pasteur & Hill 2010). While it is known that the prevalence of the disease increases with age, the actual incidence and prevalence of bronchiectasis remains unclear because there have been no recent studies in the UK since the 1950s (Weycker et al. 2005). The prevalence of bronchiectasis is also thought to vary with time, geography, differences in antibiotic prescription and the prevalence of associated disorders, from 3.7/100,000 in New Zealand to 52/100,000 in the USA (Pasteur & Hill 2010).

3.3.1 Pathophysiology of bronchiectasis

The pathophysiology and aetiology of bronchiectasis also remains poorly understood. One of the difficulties in identifying the exact aetiology of the disease is because patients can have the condition for many years before the condition is diagnosed, and identification of the cause relies on retrospective recall (Hacken N 2010; Martínez-García et al. 2011). More than 50% acquire the condition secondary to having Cystic Fibrosis (CF) (which is a progressive disease cause by an inherited defect of chromosome seven) (Pasteur et al. 2000; Pasteur & Hill 2010). One of the most widely accepted models of the pathophysiology of (non CF) bronchiectasis is termed; 'Cole's vicious cycle hypothesis' (Hacken N 2010). Cole proposed a cyclical model detailing an initial environmental insult on a background of genetic predisposition, which impairs mucociliary clearance and leads to the persistence of bacterial infection and inflammation within the bronchial tree. Continued bacterial infection leads to chronic inflammation causing damage to the lung parenchyma and impaired mucociliary mobility. The ongoing cycle of infection and inflammation are thought to be responsible for the chronic dilation and thickening of the bronchial tree (Hacken N 2010). These impairments translate physiologically into airway obstruction, impaired gas-exchange, increased dead space, skeletal muscle deconditioning and nutritional deficiencies. As a result, the symptomatic profile of patients with bronchiectasis includes; chronic cough, excessive sputum production, reduced exercise capacity,

breathlessness and impaired health related quality of life (O'Donnell 2008; Hacken N 2010; Pasteur & Hill 2010).

3.3.2 Diagnosis of bronchiectasis

The diagnosis of bronchiectasis can be challenging because the symptomatic profile such as cough, excessive sputum production and re-occurring infection and inflammation, resembles the symptomatic profile of other chronic respiratory disease, such as COPD and asthma (O'Donnell 2008; Martínez-García et al. 2011). Airflow obstruction, as characterised by a reduction in FEV₁/FVC ratio, is the most common pattern of spirometry seen in patients with bronchiectasis, although a mixed obstructive/restrictive or normal values may also be seen (Pasteur & Hill 2010). A diagnosis of bronchiectasis is usually based on the presence of clinical signs and symptoms (such as cough, excessive sputum production and haemoptysis) in combination with chest radiography. High resolution computerised tomography (HRCT) is subsequently used to confirm the diagnosis. Chest radiography and HRCT are most frequently used diagnostic tools; however chest radiography is usually the first test to be performed despite its reported deficiencies (van der Bruggen-Bogaarts et al. 1996). To date, chest radiography has been used to identify bronchial wall thickening. One of the major criticisms of the technique is because of its insensitivity to detect changes in the early stages of the disease, where inter-observer agreement has been shown to be poor (Edwards et al. 2003). Although radiography is usually abnormal, radiographic signs of bronchiectasis are usually unremarkable in the early stages of the disease (Diederich et al. 1996). Therefore, the gold standard for diagnosing bronchiectasis is based on HRCT as numerous studies have reported improved performance of HRCT over chest radiography in the early detection of bronchiectasis (Edwards et al. 2003). Findings from chest radiography and HRCT can be used interchangeably in the later stages of bronchiectasis, as the alterations on lung parenchyma become more noticeable in the more advanced stages (Chang et al. 2003).

3.3.3 Management of bronchiectasis

Like COPD and asthma, the management of bronchiectasis has both preventative and rehabilitative goals rather than cure, as bronchiectasis is a progressive disease (Hacken N 2010; Ong et al. 2011). The management of bronchiectasis can be broadly categorised as; 1) antibiotic treatment, 2) sputum clearance, and 3) rehabilitation (Pasteur & Hill 2010). Antibiotic treatment has been shown to be useful during episodes of infective exacerbations (Murray et al. 2009; Chalmers et al. 2012). During infective exacerbations, antibiotics can help to intercept the infective cycle to improve quality of life. However, given the vast range of pathogens responsible for the continuous infection/inflammation cycle in bronchiectasis, the use of antibiotics is usually unsuccessful in the long term management of the disease because of the multitude of pathogens requiring a range of antibiotics, and antibiotic resistance that occurs from antibiotic overuse (Evans & Greenstone 2003). As a consequence, a significant proportion of the management strategy for bronchiectasis is based on the non-pharmacological management (O'Neill et al. 2002; Pasteur & Hill 2010; Ong et al. 2011). Airways clearance can be conducted using a number of different techniques, however the physiotherapy active cycle of breathing has been reported as the most commonly used (O'Neill et al. 2002). Other techniques such as autogenic drainage and positive expiratory pressure have been used much less frequently (McArdle & O'Neill 2001). Although the evidence base is less convincing, Pulmonary Rehabilitation has also been found to be beneficial for patients with bronchiectasis (See chapter 4).

3.3.4 Summary of chapter three

Asthma, COPD and bronchiectasis are common chronic respiratory diseases that are associated with significant mortality and morbidity, and require ongoing clinical management. Pulmonary Rehabilitation is an evidence based intervention that has been found to be effective for patients with chronic respiratory disease in terms of improving exercise capacity, reducing breathlessness and improving quality of life. It was therefore selected as a

vehicle for testing the responsiveness of speech breathing patterns to change in a study which forms part of this thesis. The next chapter will describe and discuss Pulmonary Rehabilitation in the management of patients with COPD and bronchiectasis.

Chapter Four

Pulmonary Rehabilitation

4.1 Introduction to Pulmonary rehabilitation

Pulmonary Rehabilitation (PR) is an evidence-based, multidisciplinary management strategy for the care of patients with COPD, as well as patients with other disabling chronic respiratory diseases (BTS 2013; Spruit & Singh 2013). The bulk of the evidence for effectiveness comes from studies of patients with COPD, but there is a growing body of evidence for its value in other respiratory diseases (Bradley & Moran 2006; Spruit & Singh 2013). PR is designed to optimise physical and social performance of the patient by including a combination of exercise training, education and psychosocial support (Ries et al. 2007; NICE 2010; GOLD 2014). Clinical guidelines currently recommend that PR should be offered to individuals once significant symptoms have developed, either following an exacerbation of COPD, or later on in the disease pathway, when patients are considered as being in the advanced stages of the disorder (GOLD stage 3) (NICE 2010; BTS 2013). Randomised Controlled Trials have repeatedly shown that PR reduces dyspnoea and increases exercise tolerance (Reardon et al. 1994; Couser et al. 1995; Griffiths et al. 2000; Berry et al. 2003), improves health related quality of life (Wijkstra et al. 1995), reduces hospital admissions and reduces re-admission in patients with COPD (Morgan 2003), compared to those receiving 'usual care'. These benefits are sustained despite the fact that PR has minimal effect on lung function, as airways limitation persists throughout the natural history of COPD (Lacasse et al. 2007; Ries et al. 2007). This observation highlights the importance of PR in the care of patients with COPD, as the morbidity from COPD is largely associated with the secondary, systemic complications of the disease, which can be treated if appropriately recognised (Lacasse et al. 2007; GOLD 2014).

4.2 Content of Pulmonary Rehabilitation

Guidelines for the structure and content of PR have been recommended (BTS 2013; Spruit & Singh 2013), but in the UK there is considerable variation across programmes, because the exact format for the delivery of PR is not standardised. Practical factors such as staffing, finance and space have accounted for the variation among the existing programmes in the UK (Spruit & Singh 2013). Comprehensive, evidence based guidelines agree that all PR programmes should include a physical (exercise training) and behavioural component (breathing techniques, education, nutritional and psychosocial intervention) (Nici et al. 2006; BTS 2013).

Exercise training

Exercise training has been regarded as the cornerstone of PR, where improvements in muscle strength and exercise capacity have been observed in the absence of any significant gains in lung function (Spruit & Singh 2013). In a recent Cochrane review (Lacasse et al. 2007), a meta-analysis of 31 RCTs was conducted to establish the influence and effect size of PR on health related quality of life, functional, and maximal exercise capacity in patients with COPD. Various protocols have been used to assess exercise capacity, and in broad terms, these have been categorised according to the examination of functional exercise capacity (such as timed walk tests), and maximal exercise capacity (such as cycle ergometer tests). Examination of functional exercise capacity limited the meta-analysis to 16 trials, which examined walking distance during the six minute walk test (6MWT) (346 in the treatment arm, and 323 in the control). Based on changes using the 6MWT, the common effect was 48 metres (m) (95% CI; 32 to 65 m). This change exceeded the Minimal Clinically Important Difference (MCID) of 30m which has been established for the 6MWT (Holland et al. 2014). Significant improvements in maximal exercise capacity were also reported. Thirteen trials measured maximal exercise capacity using the incremental cycle ergometer reported a common effect of 8.4w (95%CI: 3.4 to 13.4w) (n=268 in the treatment arm and 243 controls) (Lacasse et al. 2007).

Traditionally, the measurement of the effectiveness of PR has been based on the before and after changes in exercise capacity measured using standardised field tests. However, improvements in exercise capacity are dependent upon the underlying muscle fibre morphology and structural characteristics, which have also been examined, although less frequently. Skeletal muscle dysfunction is common in patients with COPD and manifests in abnormal shifting in distribution of muscle fibre type (Whittom et al. 1998; Eliason et al. 2009). Diminished muscle cross sectional area, decreases in type 1 fibres (fast twitch) and increases in type 2 fibres (slow twitch) have most commonly been observed (Gosker et al. 2007; Eliason et al. 2009). A recent meta-analysis, aimed to determine whether fibre proportions in vastus lateralis (a thigh muscle) were associated with the severity of COPD. The authors concluded that there was a strong association between the two (Gosker et al. 2007). A progressive reduction in the proportion of type 1 fibres was positively associated with decreasing FEV₁ values ($r = 0.56$, $p < 0.001$), and FEV₁/FVC ($r = 0.57$, $p < 0.001$), and type two fibres were negatively associated with FEV₁ ($r = -0.21$, $p < 0.001$) and FEV₁/FVC ($r = -0.32$, $p < 0.001$).

There is also some evidence to suggest that there are morphologic adaptations in response to PR in patients with COPD (Vogiatzis et al. 2011). In a recent longitudinal study, Vogiatzis *et al* (2011) examined whether there was any improvement in muscle fibre morphology in response to PR, and whether the improvement depends on the severity of COPD. Vastus lateralis biopsies were performed in eight healthy adults (age and activity matched control group with no PR) and 46 clinically stable patients with varying severity of COPD, before and after they attended a 10 week PR programme, which consisted of three sessions per week. While this PR programme was different from the average PR programme (in that both the duration and intensity of the intervention were higher in the study) (Lacasse et al. 2007; NICE 2010; BTS 2013), the findings demonstrated that the pattern of muscle fibre shifting did not differ significantly across the GOLD stages. Following PR, vastus lateralis fibre mean cross section significantly increased ($p < 0.001$), while all groups were found to have a comparable reduction in the proportion of type two fibres ($p < 0.001$).

These findings demonstrate the positive influence of PR on skeletal muscle morphology in patients with COPD.

Current evidence based guidelines recommend that the exercise component should include a combination of: endurance training, interval training, resistance/strength training, upper limb and flexibility training (NICE 2010; BTS 2013; Spruit & Singh 2013). These training principles mimic those used for training healthy individuals, although the load and intensity of the exercises are tailored according to the ventilatory limitation. Despite the reported success of the exercise training component in PR, one of the major criticisms is that the majority of programmes focus on lower limb training (such as during walking and cycling tasks) even though the role of upper limb training during activities of daily living are becoming increasingly recognised (Lake et al. 1990).

Behavioural / self-management component

Education

The education component of PR is structured to promote an adaptive behaviour change in order to encourage ongoing self-management (Ries et al. 2007). According to evidence based guidelines, PR should include a combination of the following behavioural strategies: education (regarding the pathophysiology of chronic respiratory disease), breathing strategies, sputum clearance techniques, rationale for the use of medications and oxygen therapy, energy conservation techniques, nutritional advice, early recognition of exacerbations, promotion of physical activity and the use of coping strategies (NICE 2010; Spruit & Singh 2013). These strategies, together with smoking cessation advice, are usually taught by appropriately trained physiotherapists or respiratory nurses. However, the exact structure of educational content delivery has yet to be standardised across all PR programmes.

Adaptive breathing strategies

Adaptive breathing strategies used during PR will be discussed, since these have the potential to affect breathing patterns. Exercise limitation in patients

with COPD may be a direct result of the underlying ventilatory impairment present in the lungs of patients with COPD (Spruit & Singh 2013). Expiratory flow limitation contributing to dynamic hyperinflation has been specified as the mechanical consequence the disease (Casaburi et al. 1997; O'Donnell et al. 2001; Frisk et al. 2014). These physiological impairments lead to breathlessness during submaximal activities of daily living, and maintain a repeated cycle of exertional breathlessness secondary muscle deconditioning and reductions in physical activity (Nici et al. 2006; Spruit & Singh 2013).

Recently, adaptive breathing strategies have been reported to benefit exercise capacity by reducing dynamic hyperinflation (Dechman & Wilson 2004; Holland et al. 2012; Frisk et al. 2014). Improvements in overall breathing have also been documented, as breathing strategies have been shown to 'normalise' overall breathing pattern (Dechman & Wilson 2004). However, unlike exercise training, their application during PR has received little attention in the evidence based guidelines (BTS 2013). While breathing strategies have been advocated to complement behavioural adaptations during PR (BTS 2013; Spruit & Singh 2013), the lack of guidance has meant that there has been significant variability in terms of their delivery.

The stated aims of breathing retraining in patients with COPD is to normalise breathing pattern by adopting a slower respiratory rate, and prolong the length of expiration, which contributes to the overall reduction of dynamic hyperinflation (Casciari et al. 1981; Dechman & Wilson 2004; Yoshimi et al. 2012). In patients with COPD, adaptive breathing strategies have traditionally involved the teaching of 'pursed lipped breathing' (the act of exhaling through tightly pressed, pursed lips which prolongs expiration) (Dechman & Wilson 2004; Nield et al. 2007), and 'diaphragmatic breathing' to encourage more abdominal movement, which theoretically increases tidal volume (Cahalin et al. 2002).

Other breathing strategies such as 'Butekyo' breathing method (Berlowitz D 1995; Cowie et al. 2008) and yogic breathing (Cooper et al. 2003) have also been used, although the majority of trials examining the efficacy of these

techniques have been based on patients with asthma. In a recent Cochrane systematic review of breathing exercises in patients with (predominantly) severe COPD (Holland et al. 2012), 16 RCTs were included, with a total of 1233 randomised participants. A wide range of breathing exercises were included: pursed lipped breathing (three studies), diaphragmatic breathing (three studies), yoga (two studies), respiratory biofeedback (two studies), deep breathing exercise with inspiratory hold (one study), pursed lipped breathing and gymnastics (two studies) and pursed lipped breathing in combination with diaphragmatic breathing (two studies). In general, single studies examining the efficacy of pursed lipped breathing versus no treatment reported significant improvements in walking distance when assessed during the six minute walk test (6MWT) following eight weeks of training in 60 participants (mean difference 50 m, 95% CI 37.21 to 62.99 m). Similar results were also reported for diaphragmatic breathing versus no treatment following four weeks of training (mean difference 35 m, 95% CI 4.1 to 65.3 m). While these changes both exceed the minimally important clinical difference of 30 m for the 6MWT (Holland et al. 2014), the lower limit of the confidence interval for diaphragmatic breathing lies beyond the confidence interval estimate for the 6MWT (95% CI 37 m to 71 m), suggesting that the clinical significance for the efficacy of diaphragmatic breathing in COPD remains uncertain.

Walking distance following yoga breathing has been reported to result in significant improvements in the 6MWT in patients with COPD (mean difference 45 m, 95% CI 29 to 61m). However, these results were observed following three months of supervised training (Pomidori et al. 2009). Consistent effects on breathlessness and health related quality of life were not established across the trials, as outcomes were similar across all breathing exercises examined. Therefore, while breathing exercises performed over four to 15 weeks have been associated with an improvement in functional exercise capacity when compared with no intervention, their effect on other outcome measures, such as health related quality of life remains less clear.

A number of studies have used breathing techniques in combination with other therapies, or a combination of breathing therapies, making it impossible to

separate the individual effects of the breathing techniques. However, despite these drawbacks, adaptive breathing strategies including pursed lipped breathing and diaphragmatic breathing are frequently incorporated into standard PR programmes, and may contribute to the overall success of the intervention. Since the content of PR is multidimensional, it is not possible to evaluate the individual effect of breathing strategies as part of PR.

4.3 Structure of Pulmonary Rehabilitation

There is currently no conclusive evidence regarding the optimal duration of PR (NICE 2010; Beauchamp et al. 2011; BTS 2013). However the majority of studies documenting the benefits of a PR intervention have been based on programmes lasting at least six weeks in duration (Lacasse et al. 2007). Programmes should ideally include two supervised sessions per week, and a third (unsupervised) session has also been found to be beneficial (NICE 2010; BTS 2013). There is a general consensus amongst evidence based clinical guidelines that each programme should last a minimum of six weeks and a maximum of 12 weeks depending on department resources and patient demand (NICE 2010; BTS 2013). An increasing body of evidence has suggested that the longer PR programmes have a more favourable influence on patient centred endpoints (Beauchamp et al. 2011). While programmes lasting between six and eight weeks are currently not standard, the evidence supporting programmes lasting less than four weeks is less clear. This is because fewer studies with robust designs have examined the benefits of shorter PR programmes (less than six weeks), and there has therefore been an ongoing debate about the efficacy of shorter programmes (Green et al. 2001; Haave et al. 2007; Beauchamp et al. 2011)

In a previous well designed two arm RCT, 44 patients with COPD were randomly assigned into either a four (eight supervised sessions) or seven week (14 supervised sessions) PR intervention (Green et al. 2001). The study was powered for changes in health status based on changes in the Chronic Respiratory Questionnaire (CRQ), and exercise capacity was the secondary outcome. Patients who completed the seven week PR intervention had a greater

improvement in all outcome measures in comparison to those undergoing the four week programme. Statistical significance was reached for the primary outcome measure (CRQ) for the domains of breathlessness (-0.80, 95% CI -0.13 to -1.48, $p < 0.05$), emotion (-0.89, 95% CI -0.33 to -1.45, $p < 0.005$) and mastery (-0.84, 95% CI -0.10 to -1.58, $p < 0.05$). While changes in exercise capacity were shown to be higher after the seven week intervention, the differences were not found to be statistically significant. This may be because the study was not powered to detect changes in this measure.

More recently, a similar RCT examined the effectiveness of a four week versus a seven week PR intervention in 100 patients with COPD, with 50 participants in each arm (Sewell et al. 2006). Between group changes were assessed at baseline, after completion of PR (after four or seven weeks), and then six months after completion. Patients undergoing the four week intervention were also assessed at seven weeks. While statistically significant within-group improvements were found for the incremental shuttle walk test (ISWT), endurance shuttle walk test (ESWT) and the chronic respiratory questionnaire (CRQ), between-group differences were not found for any of the study outcome measures or time points. The study concluded that the benefits of a four and seven week PR programme were interchangeable. However, participants in the four week programme were also instructed to continue with unsupervised exercise between week five and seven. It is possible that the seven week assessment in participants who were undergoing the four week intervention may have positively influenced exercise compliance between weeks five and seven, making the four week intervention of similar intensity to the seven week programme.

Due to heterogeneity in study design and patient outcomes, definitive recommendations for shorter programmes (lasting less than six weeks) have not been made. Therefore, evidence based guidelines have advocated that PR programmes should ideally last between six and 12 weeks. One of the challenges for defining the optimal duration for PR is that COPD is a heterogeneous disease with multiple disease pathways and clinical presentations. The inability to define an optimal duration suggests that the

duration may need to be looked at on a more individual basis. However, limited hospital staff and resources may be the main barrier to achieving this.

4.4 Pulmonary rehabilitation for patients with bronchiectasis

Patients with COPD account for the largest proportion of all patients who are referred for PR (Troosters et al. 2010; BTS 2013; Spruit & Singh 2013). However the benefits of the intervention are becoming increasingly recognised in patients with other chronic diseases, including: bronchiectasis, asthma and lung cancer (Newall et al. 2005; Ong et al. 2011; Spruit & Singh 2013). Amongst the extrapulmonary complications of bronchiectasis, patients experience reductions in exercise capacity and health related quality of life, which occurs as a direct consequence of their ventilatory impairment (Spruit & Singh 2013). Since the underlying respiratory impairment is progressive in nature, the systemic complications of the disease can be managed if appropriately recognised. Evidence based guidelines have recommended that all patients with non-Cystic Fibrosis (CF) bronchiectasis, who have breathlessness reducing their activities of daily living, should have access to, and be considered for PR (BTS 2013).

In one RCT 32 patients with idiopathic bronchiectasis were randomly assigned to one of three groups: PR plus sham Inspiratory Muscle Training (IMT) (PR-SHAM), PR plus targeted IMT (PR-IMT), or control who received no intervention (Bradley & Moran 2006). Apart from the control group, all patients underwent an eight week PR programme (consisting of three supervised sessions per week), or PR plus IMT. Both PR-SHAM and PR-IMT resulted in significant improvements in walking distance assessed during the incremental shuttle walk test (ISWT). This was reported as 96.7 m (95% CI 59.6 to 133.7 m) and 124 m (95% CI 63.2 to 185.9 m) respectively. Both of these differences exceeded the minimally important clinical difference of 47.5 m for the ISWT (Singh & al 2014), and no statistically significant differences were found between the PR-SHAM or PR-IMT group, suggesting that IMT had no additional

benefit to PR in terms of exercise capacity. Similar findings were also found for inspiratory muscle strength. A significant increase in inspiratory muscle strength was found for both PR-SHAM (12 cm H₂O 95% CI 1.1 to 22.9 cm H₂O, p=0.04) and PR-IMT (21.4 cm H₂O, 95% CI: 9.3 to 33.4 cm H₂O, p=0.008), although the magnitude of change was similar between the two groups (p=0.22). Although the PR programme in this study was longer in duration, and more intense in comparison to standard programmes lasting six week (with two sessions per week) (BTS 2013; Spruit & Singh 2013), these findings suggest that PR is effective for improving exercise tolerance and inspiratory muscle strength in patients with bronchiectasis, while IMT has no additional benefit.

It is reported that patients with bronchiectasis respond to PR in a similar way to patients with COPD. In a recent retrospective review, 95 patients with bronchiectasis were compared with a matched COPD group who completed the same PR programme lasting six weeks in duration (Ong et al. 2011). The success of the programme was assessed according to before and after changes in exercise capacity (assessed during the 6MWT) and health related quality of life (assessed using the Chronic Respiratory Disease Questionnaire (CRDQ)). In patients with bronchiectasis, significant improvement in walking distance was reported following the intervention (mean difference: 53.4 m 95% CI 45.0 to 61.7 m, p<0.05). Significant improvements were also documented for the CRDQ (mean difference: 14.0 units, 95% CI 11.3 TO 16.7 units, p<0.05), and between-group differences were non-significant. These findings suggest that the magnitude of improvement following PR is similar in patients with COPD and bronchiectasis in terms of exercise capacity and health related quality of life. However, the influence of the intervention on other patient-centred end points, such as breathlessness, currently remains unclear as studies have yet to examine before and after changes in this domain.

4.5 Summary of chapter four

PR is a recommended standard of care in patients with COPD (BTS 2013; GOLD 2014), and more recently, the benefits of the intervention have been observed

in patients with bronchiectasis (BTS 2013). Measurable changes in a number of patient centred outcomes have been observed following the intervention, including improvements in exercise capacity, muscle morphology and reductions in breathlessness. In the next chapter the concept of speech breathing pattern is introduced, with a justification for its potential role in the monitoring of chronic respiratory diseases.

Chapter Five

Speech breathing patterns

In this chapter the concept of speech breathing pattern analysis is introduced and the effects of age, sex and the influence of respiratory disease on these patterns are discussed.

5.1 Speech breathing pattern analysis in context

Despite the evidence that breathing pattern differs between health and respiratory disease (Tobin et al. 1983b; Loveridge et al. 1986), detecting these differences **at rest** can be challenging. At rest, any alterations in breathing patterns do not become pronounced until the later stages of respiratory disease (Sassoon & Hawari 1999; Garcia-Pachon 2002), or during acute respiratory distress (Kennedy 2007). Alterations in breathing patterns in patients with chronic respiratory disease can also become more apparent under situations of increased respiratory drive, such as during exercise (Troosters et al. 2010). In patients with COPD for example, dynamic hyperinflation (exercise induced air-trapping) has been shown to place patients at a mechanical disadvantage, requiring them to generate additional inspiratory pressure to maintain tidal breathing (O'Donnell et al. 2001; Alves et al. 2008). Although measuring breathing pattern in response to physical activity could highlight changes in the earlier stages of respiratory disease, this practice is time consuming, requires specialised clinical resources (such as a treadmill, ergometer or gym) and increases the patient burden because of the time and effort associated with undergoing exercise testing.

Clinicians are aware that patients in respiratory distress often find it difficult or impossible to speak in complete sentences (Kennedy 2007; Binazzi et al. 2011). Patients become more breathless during speech because of the effort imposed by the conflict between communicational needs and respiratory demand (Loudon et al. 1988; Lee et al. 1993). Speech tasks therefore provide a way to increase respiratory demand without physical exercise. Examining

breathing patterns during speaking activities could therefore be more useful for highlighting changes in respiratory disease, in comparison to resting tidal breathing. Before speech breathing pattern analysis is examined for its respiratory monitoring potential, the physiological background and significance of speech breathing patterns in relation to respiratory disease will firstly be considered.

5.2 An introduction to speech breathing

Although the primary role of breathing is to satisfy metabolic needs, in humans it has a secondary function concerned with communication, by generating airflow and maintaining a constant subglottal pressure for the production of speech (Bunn & Mead 1971; Conrad & Schönle 1979). The development of non-invasive respiratory monitoring techniques such as RIP, have enabled the examination of speaking related breathing behaviours in children and adults. It became possible to measure breathing patterns unobtrusively without obstructing the oral and nasal cavity using facemasks and mouthpieces. 'Speech breathing' is the term used to describe the breathing patterns adopted during periods of sound production.

Like breathing pattern, the definition of speech breathing pattern lacks universal consensus, and a number of respiratory parameters have been used to describe speech breathing patterns in the literature. Historically, many of these studies have considered respiratory parameters relating to volume and flow when describing these patterns (Hixon 1973; Hoit & Hixon 1987; Sperry & Kilich 1992). However, obtaining accurate measures of volume and flow requires the use of a flow meter and the calibration of RIP using spirometry, which can be time consuming, requires participant co-operation and limits usefulness in community settings. Respiratory timing components (such as inspiration and expiration time measured in seconds), or chest wall contributions, have been less frequently used to characterise speech breathing, even though speech significantly alters the timing components of breathing.

The next sections will examine some of the aspects of normal speech breathing patterns in adults.

5.3 Normal speech breathing patterns

It is known that the breathing patterns used for ventilation differ from the breathing patterns produced during speech (Bunn & Mead 1971; Conrad & Schönle 1979). In resting breathing, the rhythmic alternation between inspirations and expirations are largely equal for each phase in terms of velocity and volume (Tobin et al. 1983a; Winkworth et al. 1995). However, during speech, breathing patterns are altered in favour of communication, while still serving to meet metabolic demand, creating what has been referred to in the literature as the ‘saw tooth pattern’ (figure 3) (Bouhuys et al. 1966; Hixon 1973).

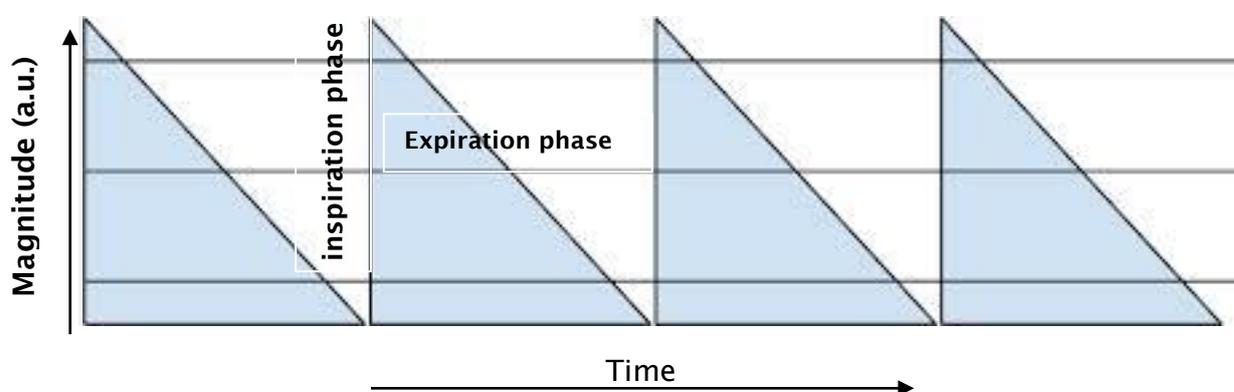


Figure 3 Schematic representation of the speech breathing pattern referred to in the literature as the ‘saw tooth’ pattern (Bouhuys et al. 1966)

Speech breathing cycles are characterised by having a short and fast inspiration followed by a slow and prolonged expiration phase, with larger lung volume excursions and a higher and more sustained expiratory pressure (Bunn & Mead 1971; Hixon 1973; Hixon et al. 1973; Conrad & Schönle 1979; Hodge & Rochet 1989; Hoit & Lohmeier 2000). In healthy individuals, this

breathing pattern has been described as the most efficient for communication purposes. The short inspiration phases reduce the silences, while the prolonged expiration phases extends the time available for sound production (Hixon 1973; Loudon et al. 1988; Hoit & Lohmeier 2000).

Speech breathing studies have primarily taken two forms; the physiology of speech breathing patterns, and the linguistic influence of respiratory control, where the latter has formed the majority of the research. The influence of different types of speech on breathing pattern have been examined during spontaneous speech, where participants were asked to converse about a topic of choice (Winkworth et al. 1995); oral reading from a pre-written text (Winkworth et al. 1994); counting in time to a metronome (Loudon et al. 1988; Lee et al. 1993) and describing an image (Loudon et al. 1988). Although there are some issues with methodology within the speech breathing literature (which are discussed later in this section), it has been generally accepted that in healthy adults, speech breathing patterns elicit 'task-specific' behaviours during different types of speech production (Loudon et al. 1988; Lee et al. 1993; Moore et al. 2001; Bailey & Hoit 2002), specifically if the speech is constrained (during oral reading) or un-constrained (during spontaneous speech). However this observation has yet to be confirmed in patients with chronic respiratory disease.

It has been reported that the location of inspiration phases during reading tasks is nearly always at structural boundaries or 'grammatically appropriate' locations (Winkworth et al. 1994; Winkworth et al. 1995). In an early study by Henderson *et al* (1965), the location of inspiration phases was examined in relation to their structural location in 10 healthy adults during oral reading and spontaneous speech. In comparison to the reading task, where inspirations were always taken at structural boundaries (or structural clauses), during the spontaneous speech task only 69% of the inspiration phases were located at grammatically appropriate junctions. These findings are in broad agreement with a more recent study by Wang *et al* (2010), who reported that the proportion of grammatically inappropriate inspiration phases was 1.8 % during a reading task, and 13% during spontaneous speech. The difference in the

reported proportion of grammatically inappropriate inspiration phases during a spontaneous speech task in each of these studies may be explained by the different techniques used in each study to obtain breathing pattern. Wang *et al* (2010) used a circumferentially vented mask connected to a PNT to record breathing patterns, while Henderson had used RIP. Such methodological differences highlight the difficulties faced when generalising the findings from speech breathing studies, as have used different sample sizes, speech tasks and techniques to obtain breathing pattern (Wang *et al.* 2010).

Some studies have used volume indices to discriminate between the breathing patterns produced during different speech tasks. Russell and Stathopoulos (1988) reported that the mean tidal volume (estimated with RIP and expressed as a percentage of the vital capacity (VC)) during reading was 39% of VC. This was in broad agreement with Winkworth *et al* (1995), who also reported tidal volume expressed as a percentage of the vital capacity (VC) during reading and spontaneous speech, and found that spontaneous speech was associated with greater expired volumes (51% of VC), compared with reading (41% of VC). In explanation, Winkworth *et al* (1995) concluded that spontaneous speech enabled participants to vary their sentence lengths without the restrictions imposed by pre written text, which could in turn allow them to increase their 'breathing variability'. However, measurements of absolute tidal volumes require calibration with a spirometer. The process is time consuming and face masks and mouth pieces have been poorly tolerated in children and patients with breathing difficulties (see section 2.3.9). Therefore, while absolute measurements of tidal volume have been used to characterise speech breathing patterns in research studies, their use in ongoing respiratory monitoring may be limited because of the challenges associated with measuring them.

A further limitation of these studies is that many of them have not controlled for physiological or anthropometric factors. This may be an issue because some studies have suggested that speech breathing patterns alter in response to age (Hoit & Hixon 1987; Russell & Stathopoulos 1988), and sex (Hoit *et al.*

1989) . The next two sections will therefore consider the influence of age and sex on speech breathing patterns.

5.3.1 The influence of age on speech breathing patterns

Age related changes in respiratory physiology have been shown to coincide with a progressive decrease in respiratory performance over time (Janssens et al. 1999; Watsford et al. 2007). However, in the absence of respiratory pathology, the ageing lungs are able to maintain adequate gas exchange in order to satisfy metabolic demands (Lee et al. 1993; Verschakelen & Demedts 1995; Watsford et al. 2007). Reductions in pulmonary elastic recoil, respiratory muscle strength and overall chest wall compliance are amongst the major age reported physiological changes (Lanteri & Sly 1993; Tolep & Kelsen 1993; Janssens et al. 1999). Other general changes include osteoporotic changes, which reduce the height of the thoracic vertebrae, and hardening of the rib cage from calcification and kyphosis which reduce the ability of the chest wall to expand during inspiration (Hoepfner et al. 1984). Speech and breathing share the same anatomical structures, and these age-related pulmonary changes have been shown also to influence speech production. For example, with reductions in pulmonary elastic recoil, older adults have been shown to compensate by initiating speech at higher lung volumes in order to use the higher recoil pressure, which ultimately requires greater inspiratory effort (Huber 2008).

There is also some limited evidence to suggest that speech breathing patterns alter with age. To date, however, the majority of speech breathing research has been conducted with young males (Hoit & Hixon 1987; Binazzi et al. 2006). Hoit & Hixon (1987) investigated the age-related changes in speech breathing parameters relating to volume in 30 healthy men from three different age groups (25, 50 and 75 years) by simultaneously measuring speech breathing patterns during a spontaneous speech and a reading task, each lasting five minutes. Breathing parameters were extracted from a period of 10 – 20 breath cycles. When examining linguistic performance, differences were more apparent when contrasting the younger group (25 years) with the two older

groups (50 and 75 years). The older groups used significantly fewer syllables per breath cycle and expended greater average lung volume per syllable, and had larger lung volumes and ribcage excursions, compared with the younger group. These differences were thought to reflect respiratory compensation in response to the reduced elastic recoil pressures available to generate subglottal pressure for speech (Hoit & Hixon 1987) .

Initiating speech at higher lung volumes has also been suggested to enable individuals to have longer breathing cycle durations during speech, as older adults have previously been shown to produce shorter breathing cycles during reading and spontaneous speech (Sperry & Klich 1992). Huber *et al* (2008) suggested that the production of a shorter breath cycle is a compensatory mechanism for reduced functional reserve. While these studies have highlighted the potential influence of age on speech breathing patterns, it is not clear if age is an independent factor for inducing changes in speech breathing patterns. The findings by Hoit and Hixon (1987) may have been influenced by sampling bias. In their study between 10 and 20 breath cycles were selected for statistical analysis. However, the selection process for choosing these cycles from the five minute recording period was not explained, and it was not clear whether the researchers who conducted the analysis were blinded to the different age groups. Any awareness of the age groups during the breath selection process would have had the potential to introduce an element of subjective sampling bias. Another general factor (seen in a number of speech breathing studies), relates to their analysis of a very small sample of breaths. Although the stability of speech breathing patterns is currently unquantified, resting breathing patterns have been associated with a high level of variability due to the influence of a number of internal and external factors (see section 2.2.3). Therefore an analysis of speech breathing patterns based on a selection of 10-20 breaths may be limited in validity. Although age would not affect within-subject studies, it needs consideration when comparing between groups. Despite the association between reduced respiratory performance and increasing age (Janssens et al. 1999; Watsford et al. 2007), the influence of age on speech breathing patterns is not certain, and

the many speech breathing studies to date have not controlled for age or considered this factor as a potential confounder.

5.3.2 The influence of sex on speech breathing patterns

The influence of sex on the development of the lungs and susceptibility to respiratory pathology has been recognised in terms of biological factors and social differences (Becklake & Kauffmann 1999; Carey et al. 2007). Production of surfactant in neonatal lungs has been shown to occur earlier in females compared to males (Fleischer et al. 1985). In premature infants, surfactant deficiency is a major cause of Respiratory Distress Syndrome (RDS), where male infants have been shown to have a higher risk of developing the syndrome compared to females (Doershuk 1974; Ingemarsson 2003). Structural differences between sexes in adults have also been noted, particularly with reference to the size and volume of the lungs, as males have been shown to have a greater lung capacity compared to females, due to their overall larger size (Becklake & Kauffmann 1999).

Based on the evidence of sex related differences in respiratory development and anatomical differences, a small body of research has suggested that speech breathing patterns may also be influenced by sex. Hodge & Rochet (1989) reported that abdominal contribution to overall changes to lung volume was greater in healthy male participants than in females during quiet breathing and reading (Hodge & Rochet 1989). However, apart from differences in chest wall movements, the evidence that other speech breathing parameters are influenced by sex is less clear. Binazzi *et al* (2006) examined the speech breathing patterns during reading, singing and loud whispering in a group of 10 young men and 10 young women, where lung volumes and chest wall kinematics were extracted using OEP. Although expiratory time per syllable was on average shorter in females' compared to males, when these measures were normalised for Vital Capacity (VC), no differences were found. These findings therefore suggest sex related differences could be more reflective of physical characteristics. It is possible that females have shorter expiratory time per syllable because of the relationship between lung capacity and height,

because the females may have had a smaller lung capacity in line with their height (Hepper et al. 1960).

5.3.3 Summary

A number of internal factors (such as age and sex) and external factors (such as the type of speech spoken) have been suggested to influence speech breathing patterns in healthy adults. However, while speech breathing patterns have been repeatedly shown to alter in response to the type of speech spoken in healthy adults (Winkworth et al. 1994; Wang et al. 2010), the influence of age and sex is less clear because of the methodological differences between published studies.

Speech breathing research has been a relatively neglected area of enquiry, even though there is some evidence that speech breathing patterns are different between health and respiratory disease (Loudon et al. 1988; Lee et al. 1993). Some of these differences will now be considered in the final part of this chapter.

5.4 Speech and Respiratory disease

Speech can be almost effortlessly sustained in healthy individuals because they are able to adapt their breathing cycles to support shorter inspirations and longer, more sustained expiration phases (Winkworth et al. 1995). However, adapting breathing cycles to accommodate speech becomes increasingly challenging in the presence of respiratory impairment, because of the competition imposed between communication and metabolic demand (Loudon et al. 1988; Hodge & Rochet 1989; Lee et al. 1993). The following section will examine the evidence that speech breathing patterns alter in the presence of respiratory disease, where the normal aspects of speech and ventilation will firstly be considered.

5.4.1 Speech and ventilation in healthy individuals

In healthy individuals, ventilation has been shown to increase during speech above the levels required for quiet breathing alone (Bunn & Mead 1971). Speaking has therefore been shown to be associated with ‘hyperventilation’ (Bunn & Mead 1971; Russell et al. 1998; Hoit & Lohmeier 2000), which is defined as a state of breathing faster or deeper than normal, in excess of metabolic requirements (Hough 2001).

In an early study, Bunn and Mead (1971) compared the levels of ventilation during speech production and quiet breathing by examining the end-tidal carbon dioxide (ETCO₂) (a non-invasive measurement of exhaled carbon dioxide (CO₂)) (St. John 2003). Seven healthy participants were each asked to sit in an air-cooled plethysmograph (an enclosed chamber), with an air tight seal at the neck separating the body and the head chambers. Volumes were measured with a spirometer that was attached to the body chamber. End-tidal CO₂ levels were measured from a sampling tube that was placed directly in front of the participants’ nose, during reading and quiet breathing tasks, each lasting five minutes. Although the measurement of ETCO₂ levels has become a surrogate for more invasive methods (such as arterial blood gas analysis) (Tobias & Meyer 1997), the interpretation of ETCO₂ is influenced by behavioural factors, such as mouth breathing and speech. One of the major limitations associated with measuring ETCO₂ using a nasal sampling tube is because the measurement does not capture any ETCO₂ that is expelled when breathing through the mouth, possibly leading to inaccurate measures of ETCO₂. However, while this criticism was not acknowledged in their study, one of the major findings was that the reading task was associated with a significant reduction in ETCO₂ levels in six of the seven participants, compared with resting breathing.

Physiologically, ETCO₂ becomes reduced during high ventilatory drive and increased respiration, when ventilation exceeds metabolic demands, causing individuals to ‘blow away’ CO₂. Participants had a slower average respiratory rate during speech (mean = 14 bpm) compared to quiet breathing alone (mean

= 19 bpm). The Authors' concluded that since ETCO_2 was found to be reduced during speech, this suggests that the speech task was associated with increased ventilation to the alveoli, so their tidal volumes must have increased. A slower respiratory rate combined with increased volume increases the fraction of inhaled gas which reaches the alveoli.

These findings indicate that speech increases ventilatory requirements, even in healthy individuals. However, while healthy individuals are able to withstand the increase in ventilatory demand imposed by speech, patients with respiratory impairments are less able to do this. As a consequence, speaking related breathlessness is a common manifestation in patients with chronic respiratory disease, which becomes worse with increasing respiratory impairment (Hoit et al. 2007; Kennedy 2007; Binazzi et al. 2011).

5.4.2 Speaking related breathlessness in patients with respiratory disease

It is recognised that speaking related breathlessness is a common clinical problem (Kennedy 2007). A comprehensive survey examining COPD in the US revealed that 32% of patients with COPD become short of breath while speaking (Britton 2003). Patients with COPD have reported breathlessness as being the principle factor for limiting their ability to function on a day to day basis, and they have been shown to experience more breathlessness during combined physical and speech activities compared to speech alone (Mahler & Wells 1988). In extreme cases, the inability to speak in full sentences due to breathlessness can be an indicator of acute patient deterioration (Kennedy 2007).

There is also some evidence to suggest that speaking related breathlessness is responsive to PR for patients with COPD (Binazzi et al. 2011). In recent interventional study, Binazzi *et al* (2011) evaluated the level of self-perceived breathlessness in 31 patients with mild to severe COPD before and after a four week PR intervention consisting of six sessions per week. Breathlessness during speech was evaluated using a ten point questionnaire previously

proposed by Lee *et al* (1998). Each questionnaire item depicted a situation related to speech production, such as 'having a conversation with someone' and 'talking on the phone', where patients were asked to rate each item based on their perception of breathlessness. Information relating to functional walking distance (assessed during the six minute walk test) and exertional dyspnoea (assessed using a five point Medical Research Scale (MRC) scale) were also assessed in order to evaluate the efficacy of the PR programme. In line with previous findings, significant improvements in functional walking distance ($p < 0.0001$), and exertional breathlessness ($p < 0.0001$) were observed following the intervention. However, the novel findings from their study was that breathlessness during speech was responsive to a four week PR programme, as level of breathlessness during speech was found to significantly reduce following the intervention (%max before PR = 60.3 ± 23.2 , after PR = 43.7 ± 19.7 $p < 0.0001$). However, despite these apparent positive findings, one of the main criticisms of the study was the PR programme involved six sessions per week for a total of four weeks. While the optimal intensity for PR has not yet been defined (Beauchamp *et al.* 2011), this intensity exceeds the number of sessions advocated in recent evidence based guidelines (between two and three sessions per week) (NICE 2010; BTS 2013). Furthermore, while the authors claimed that breathlessness during speech was an independent outcome measure following PR, this tool has limited application in objective respiratory monitoring because of the subjectivity associated with rating perceived breathlessness. In some respiratory conditions, such as asthma, personal perception of symptoms can be poor and does not correlate well with the severity of acute bronchoconstriction induced by methacholine challenge testing (Reck *et al.* 2010). While it is clear that level of speaking related breathlessness is associated with increasing or decreasing respiratory impairment (Hoit *et al.* 2007), questionnaires only provide subjective information about breathing patterns during speech.

5.4.3 Speech breathing patterns and respiratory disease

Recording perceptions of breathlessness is a subjective practice and has limited application for objective respiratory monitoring. In contrast, speech breathing pattern analysis can quantify the parameters of breathing pattern during speech. A very small body of evidence (two studies) has suggested speech breathing patterns are fundamentally different in health and disease (Loudon et al. 1988; Lee et al. 1993). These two studies will now be reviewed in detail.

Louden *et al* (1988) compared the speech breathing patterns produced by 10 healthy participants (mean age: 38.6 ± 16.26 years) and 14 patients with varying degrees of asthma (mean age: 40.92 ± 14.26). Breathing patterns were recorded noninvasively using RIP during three different speech tasks each lasting five minutes. They were; spontaneous speech, describing a picture and counting with a metronome from 1 to 100. Speech was simultaneously recorded using a microphone which was placed directly in front of the participants' mouth, and participants were positioned on a tilt table at an angle of 15 degrees, from vertical towards supine. This decision was taken so that participants were 'distracted' away from the recording equipment. However, the positioning of participants at a 15 degree angle from vertical towards supine is an unnatural task, and may have actually increased their focus on the recording equipment. As previously discussed, awareness of breathing pattern measurement might alter natural breathing patterns (Han et al. 1997), however this was not considered in their study.

Breathing parameters relating to respiratory timings and volumes were manually extracted from the raw data files using aural detection of each breathing cycle. While the exact process of calculating each breathing parameter was poorly described in the paper, voice recordings that corresponded to the RIP data were played from a cassette player. The researcher used the speech to determine the presence of a breath in relation to the RIP signal which was displayed on an oscilloscope. This method of breathing cycle detection is now considered to be technologically dated. The

detection of breaths was not automated, and relied on the hearing ability of the researcher to detect the speech signal. One of the issues concerning the aural detection of breathing cycles relates to the subjectivity associated with determining the start and end of each breathing cycle, raising doubt about the objectivity of the data. Furthermore, while each speech task was recorded for a period of five minutes, the number of breathing cycles extracted for analysis differed between the tasks. Fifty breathing cycles were analysed for both the describing and conversation tasks, while 25 breathing cycles were analysed for the counting task. However, a justification for these differences was not provided, nor did the paper clarify how the breathing cycles were selected from the five minute speech recordings. This potentially exposed the data to a further element of subjectivity, which was not addressed.

One of the major findings of the study was that during the describing task, patients with asthma had a significantly longer inspiratory time, shorter expiratory time, and shorter breathing cycle time in comparison to healthy adults ($p < 0.05$). While the same trend was observed during the conversation and counting tasks, the differences between the two groups were not found to be statistically significant for breathing cycle time during the counting task ($p = 0.29$), or inspiration time during the conversation task ($p = 0.10$). Differences between the two groups were also found for end-expiratory volumes (%VC), where patients with asthma were found to have a significantly greater end-expiratory volume when compared to healthy adults during the describing (patients: $55.12 \pm 16.57\%$, healthy: $44.91 \pm 17.81\%$, $p = 0.01$) and counting tasks (patients: 58.47 ± 24.96 , healthy: $38.85 \pm 11.53\%$, $p = 0.00$). However, no differences were found for the conversational speech task ($p = 0.08$), possibly because the study was insufficiently powered.

Although a number of concerns have been raised regarding the method that were used to measure speech breathing patterns (such as positioning on a tilt table) and extract breathing cycles, Louden *et al* (1988) concluded that the differences between healthy adults and patients with asthma were reflective of the underlying respiratory impairment. Speech breathing patterns in patients with asthma are characterised by adopting a longer inspiratory phase and

shorter expiratory phase in comparison to healthy adults. As a consequence, these patients were 'forced' to adapt their speech behaviour so they could prioritise ventilation. These theories were supported by the observation that healthy adults were able to devote a greater proportion of the respiratory cycle to speech (3.03 ± 0.69 seconds), compared with patients with asthma (1.79 ± 0.84 seconds) ($p=0.000$).

These findings demonstrate the adaptation of speech breathing patterns in response to respiratory impairment, and suggest that the examination of respiratory timing components during speech breathing could be sensitive to changes in lung health. Monitoring respiratory timing components during speech breathing could therefore provide an indication of changes associated with respiratory disease. However, these parameters have yet to be considered during the monitoring of respiratory disease.

In a similar study, Lee *et al* (1993) hypothesised that different respiratory diseases are characterised by 'disease specific' speech breathing patterns, consistent with the structural influences that different respiratory diseases have on the lungs. To examine this possibility, 41 patients with various respiratory diseases (asthma $n=14$ (mean age: 40.9 ± 13.8 years), emphysema (COPD) $n=15$ (mean age: 62.5 ± 8.95 years), sarcoidosis $n=12$ (mean age: 37.5 ± 8.89 years) and 16 healthy participants (mean age: 39.8 ± 14.0 years) underwent a similar speech breathing protocol described by Loudon *et al* (1988). Speech and breathing patterns were recorded non-invasively using RIP during a five minute period of spontaneous speech, and of counting from 1-100. Fifty consecutive breathing cycles were then manually extracted from each five minute recording, where breathing cycles were identified by replaying the corresponding speech segment from an audio cassette. Concerns regarding the aural detection of breathing cycles have previously been discussed, however these concerns were also not addressed in this study.

Using breathing pattern data relating to respiratory timings and volumes, discriminant function analysis (which is a statistical test that is used to identify variables that can discriminate between two or more naturally occurring

groups) was applied, and two variables (inspiration time/total time ratio and expiration time) emerged from the analysis as the best predictors of group membership. Although the study concluded that speech breathing patterns were 'disease specific', using these two variables, it was reported that only 54.4% of the participants were classified into the correct disease category, which suggests that classification was not much better than chance. Furthermore, it was reported that the discriminant function analysis was least successful at correctly allocating patients with sarcoidosis (25%), while healthy participants were allocated correctly more frequently (69%). One possibility for this variability could be because patients with sarcoidosis were less physiologically impaired. Their FEV₁(%) (79.5±7.49) was similar to the healthy participants (78.3±7.89). It is therefore possible that patients with sarcoidosis were wrongly classified because their lung function was similar to the healthy participants. These findings suggest that speech breathing patterns might be influenced by disease severity, rather than diagnostic category.

Since speech breathing pattern research in patients with respiratory disease has been a relatively neglected area of enquiry, the techniques used to extract speech breathing parameters in these early studies are now considered to be technologically dated. This is because the manual extraction of breathing cycles from the RIP data is a subjective process, and could increase the chance of human error. However, since recognisable differences have been reported between speech breathing patterns obtained from healthy adults and patients with various chronic respiratory diseases, these observations warrant further investigation.

5.5 Summary of chapter five

The potential for speech breathing pattern analysis to be used as an objective marker of respiratory health has been discussed. At present, speech breathing research has been restricted to the examination of single time point measurements in patients with respiratory disease. It is therefore uncertain if, or how speech breathing patterns alter over time, as the stability of these parameters has yet to be examined either in response to progressive

respiratory deterioration, or in response to a therapeutic intervention with a sound evidence base for effectiveness.

Before exploring possible responses in speech breathing pattern to an intervention, it was first necessary to determine the optimal speech breathing protocol and analysis to use, and obtain some comparative normal data. The first study reported in this current work therefore involved the characterisation of speech breathing patterns in a convenience sample of adults, some of whom were healthy and some of whom had a self-reported history of asthma. The second study involved characterising speech breathing patterns in healthy older adults. The aim of the third study was to explore speech breathing patterns before and after a clinical intervention. It was not possible, however, within the PhD funding envelope to set up and run a randomised controlled trial, so a pragmatic decision was taken to undertake an observational study in which speech breathing patterns were recorded before and after a Pulmonary Rehabilitation (PR) programme. Based on the knowledge that PR is often associated with an improvement in exercise capacity and reduced breathlessness (Lacasse et al. 2007; Ries et al. 2007), and that breathing pattern training forms part of PR programmes (Spruit & Singh 2013; BTS 2014), it was hypothesised that these changes might be associated with changes in speech breathing patterns. The third study involved patients with chronic respiratory disease (COPD and bronchiectasis), where speech breathing patterns were recorded before, during and after a six week PR programme. These three studies are all described in the next chapter.

Chapter Six

Method

In this chapter, the methods that were used in this research are described in relation to the procedure, and justification for the selection of participants and equipment is provided. The plan for statistical analysis based on the data that were gathered from all three studies has been presented at the end of this chapter.

Introduction

Breathing and speech breathing pattern data were collected during three studies:

In the **first study**, a cross sectional design was employed primarily to: a) characterise and explore breathing and speech breathing patterns within a heterogeneous group of 40 adults recruited from a university population, b) examine the feasibility of obtaining breathing and speech breathing patterns in relation to the protocol before applying it to a diagnosed patient population, c) optimise the speech breathing protocol and analysis plan. Within the sample recruited to this study were 29 'healthy' adults (mean age: 33.7 ± 12.85 years) and 11 adults with a self-reported history of asthma (mean age: 28.55 ± 6.15 years).

In the **second study**, breathing and speech breathing pattern data were obtained from a group of 20 healthy older adults (mean age: 66.90 ± 8.49 years), to explore the characteristics of speech breathing patterns in an healthy older population and to determine whether age had any significant influence on them.

In the **third study**, breathing and speech breathing patterns were collected from a sample of 20 patients with chronic respiratory disease before, during and after they attended a six week PR programme. Within this sample were 14 patients with COPD (mean age: 69.36 ± 9.64 years) and six patients with bronchiectasis (mean age: 70.50 ± 7.23 years).

6.0 Research aims

Data obtained from all three studies conducted in this body of research were used to achieve the specific aims outlined below:

1. To examine the feasibility of recording speech breathing patterns during different types of speech using a semi-automatic algorithm to extract breathing parameters from the raw data files.
2. To determine whether breathing and speech breathing parameters remained stable across short recording periods in healthy younger adults.
3. To determine whether age or sex had any significant influence on breathing and speech breathing parameters in healthy adults during quiet breathing, reading and conversational speech.
4. To characterise breathing/speech breathing patterns within specific participant cohorts; healthy younger adults, healthy older adults, adults with self-reported asthma, and patients with COPD and bronchiectasis, during quiet breathing and different types of speech (reading, describing, conversation and counting).
5. To characterise breathing speech/breathing pattern variability in healthy adults and patients with chronic respiratory disease during quiet breathing and different types of speech (reading, counting, describing and conversation).
6. To examine the task specificity of breathing and speech breathing within all participant cohorts detailed in aim 4.
7. To examine whether breathing and speech breathing patterns could be used to differentiate between health and chronic respiratory disease (between healthy younger adults and younger adults with self-reported asthma, and between healthy older adults and patients with COPD and bronchiectasis).
8. To examine whether the type of speech influenced the detection of any differences between healthy older adults and patients with chronic respiratory disease.
9. To examine whether breathing and speech breathing patterns were disease specific (between patients with COPD and bronchiectasis).

10. To assess whether clinical measures (Modified Borg Scores and walking distance) changed following a six week PR programme in patients with chronic respiratory disease.

11. To assess whether breathing and speech breathing patterns altered following a six week PR programme in patients with chronic respiratory disease.

To provide clarity, the methods described in this chapter have been presented according to each study. However, since similar methods were used throughout each data collection phase, each study will refer back to the section where a method was originally described in an attempt to avoid repetition.

6.1 Study one

Breathing and Speech breathing patterns in adults

6.1.1 Design

A cross sectional design was employed in order to obtain a ‘snap-shot’ measurement of breathing and speech breathing patterns from a heterogeneous sample of adults. Willing volunteers were invited to attend a single recording session at the University of Southampton.

6.1.2 Participant selection and setting

Adults over the age of 18 were eligible to participate in the study, where no specific exclusion criteria were defined. This was an exploratory study which aimed to recruit a heterogeneous sample in order to characterise the data and optimise the protocols used for measuring speech breathing patterns, before applying the protocol to a patient population. Previous speech breathing studies have been restricted to examining speech breathing parameters according to specific characteristics including: age (Hoit & Hixon 1987), sex (Hodge & Rochet 1989; Hoit et al. 1989), and body type (Hoit & Hixon 1986). Since there is no clear agreement as to what variables affect speech breathing, all participants over the age of 18 who were able to sign for consent were

included in the study. All data collection took place in a room within the Faculty of Health Sciences at the University of Southampton.

6.1.3 Recruitment procedure

It was anticipated that the university staff and students would provide an adequate pool of individuals over the age of 18. Permission was gained from the Heads of individual Schools prior to participant recruitment and posters were placed around the university (appendix 1). Anyone who was interested in taking part in the study was advised to make contact with the researcher via telephone or email using the address that was provided at the bottom of posters. Upon contact, the researcher verbally checked whether the participant met the appropriate inclusion criterion (they were over the age of 18), and then made a convenient appointment with the participant to attend a single recording session. Participants were advised that the data collection procedure would take approximately 40 minutes and were subsequently emailed a Participant Information Sheet (appendix 2).

6.1.4 Sample size

Sample size calculations were not considered appropriate because no *a priori* hypotheses had been developed for this exploratory study. It was therefore not possible to estimate the sample size needed to test them. Data obtained from the first study were used to explore and characterise speech breathing data, and optimise speech breathing protocols before applying it to a patient population. A convenience sample of forty participants was recruited to characterise speech breathing patterns in a heterogeneous sample.

Hypotheses were later developed and retrospective power calculations were performed to estimate the sample size required to test them in future studies (see Appendix 3 and Chapter Eight). Unlike simple outcome measures, which are unitary in nature (such as walking distance measured in metres), breathing pattern is complex and comprises multiple components relating to timing, volume, flow and regional contributions of the rib cage and abdomen. There are also multiple types of speech tasks that can be used to measure speech breathing patterns. Power calculations require a single primary outcome

measure. So before retrospective power calculations could be used to estimate the sample size required for future studies, there was firstly a need to select one breathing parameter and task on which to base the power calculations. A decision was made to base the retrospective power calculations on respiratory rate during a conversational speech task for the following reasons:

1. Unlike many parameters of breathing pattern which lack any well-defined normal limits, the normal range for respiratory rate has been defined in standard medical text books (Hough 2001).
2. Respiratory rate is routinely used in the assessment of respiratory and non-respiratory conditions.
3. Respiratory rate is a more robust measure, as it is longer in duration than the component parts of the breath cycle, so any measurement errors would only produce a small percentage variance in the overall mean.
4. The findings from the research in this thesis revealed that a conversational speech task was the most useful task for highlighting the differences between health and disease.

A summary of the retrospective power calculations (based on respiratory rate) that were performed in order to estimate the sample size required for a future study can be found in Appendix 3. These tables also provide the sample size required for future studies based on three additional breathing parameters representing respiratory timing, magnitudes and chest wall contributions (expiration time, expiration magnitude and the regional contribution of the ribcage to expiration (%RCExp) – see section 7.5.2 for justification for the selection of breathing parameters). These were estimated in order to demonstrate the variability in the sample size required for different breathing parameters.

Of the 40 participants who were recruited, 11 reported having a history of asthma. This was anticipated because of the prevalence of asthma in the UK adult population (European Respiratory Society 2015). The two groups have been analysed separately, even though a diagnosis of asthma was not confirmed by a clinician. For further discussion on this point see section 8.6.2

Speech breathing patterns have previously been shown to be significantly different between healthy adults and patients with asthma (Loudon et al. 1988; Lee et al. 1993).

6.1.5 Equipment and set up procedure

Breathing and speech breathing data obtained during the three studies were collected using the same procedure and equipment for recording speech breathing patterns. Any exceptions to the research protocol will be described individually per study.

6.1.5.1 Measurement of breathing pattern using Respiratory Inductive Plethysmography

Following a review of the literature examining the available non-invasive respiratory monitoring tools (section 2.3.4), a decision was made to use Respiratory Inductive Plethysmography (RIP) to acquire breathing pattern data, for reasons provided in section 2.4.

An Inductotrace® system (Ambulatory Monitoring Inc.) based on RIP technology, was used to acquire respiratory signals. Two elasticised belts (Inductobands) that were embedded with wires were fastened around the rib cage and abdomen of each participant (figure 5). Inductobands were connected to a calibration unit (Inductotrace system, Ambulatory Monitoring Inc.) via a transducer oscillator. A custom-built analogue-to-digital (A-D) converter was used to convert this signal into digital form on a laptop computer. The specific details of the A-D converter system have been provided in table 2. Respiratory signals were recorded directly into the memory of a laptop computer with custom-built software written in Matlab®.

Feature	A-D converter specification
A-D conversion rate	10kHz per channel multiplexed
Accuracy	12bit-multiplexing ADC
LSB significance	1 mV

Table 2. Specification of the A-D converter that was used in study one, two and three

6.1.5.2 Calibration of Respiratory Inductive Plethysmography (RIP)

Qualitative Diagnostic Calibration

For the reasons outlined in section 2.4.1, a decision was made to calibrate all breathing and speech breathing pattern data (from study one, two and three) using the QDC procedure, which was embedded within the peak detection algorithm (see section 6.1.7). Calibration of all data was performed retrospectively when breathing parameters were extracted from the raw data files, using the same calibration procedure in order to maintain consistency across the data. This became particularly important when performing comparative analyses. Applying the same calibration procedure to all data (healthy young, healthy old, self-reported asthma, COPD and bronchiectasis) meant the findings would not be confounded by the calibration procedure.

6.1.5.3 Measurement of speech

Technical characteristics of the head-set microphone

Speech signals were acquired from a head-set microphone (Yoga Electronics, lightweight headset EM-174M), which was placed directly in front of the participant's mouth (figure 4). The sensitivity of the microphone had an average value of -68dB. This could vary by +/- 3 dB over the frequency range 100 Hz to 16 kHz that is, if a sound of fixed power was played, but over a range of frequencies the gain (amplification) would be -68 dB, with an error in that gain of +/- 3dB.



Figure 4 Placement of the head-set microphone used to record speech signals

Justification for the selection of the head-set microphone (Yoga Electronics, lightweight headset EM-174M)

The head-set microphone was selected for its ability to represent typical microphones (such as those used by people to make ‘Skype’ calls). The technical features of the microphone were not high performance in order to replicate the conditions likely to be encountered in a practical and cost-effective measuring system. If speech breathing pattern analysis were to become considered as respiratory monitoring tool in the future, the ability for the equipment to be user-friendly and inexpensive, while still enabling the analysis of breathing patterns during speech, would be advantageous.

From a data extraction perspective, the study needed to determine whether it was possible to develop an algorithm that was robust against low quality recording conditions, which are typical of a clinical or home environment. The aim of collecting the speech data was not to perform acoustic analysis of the speech itself. Instead, the speech signals were used only to manually adjust the breathing cycles found in the corresponding RIP signal. The data extraction process is discussed in detail in section 6.1.7, but in brief, a peak detection algorithm was used to identify the beginning and end of each inspiration phase from the RIP signal. The corresponding speech signal was primarily used as additional evidence to determine whether the speech was absent or present at the boundaries of each inspiration phase. Therefore, the quality of the speech signal did not affect the ability to detect each inspiration phase.

6.1.5.4 Equipment set up

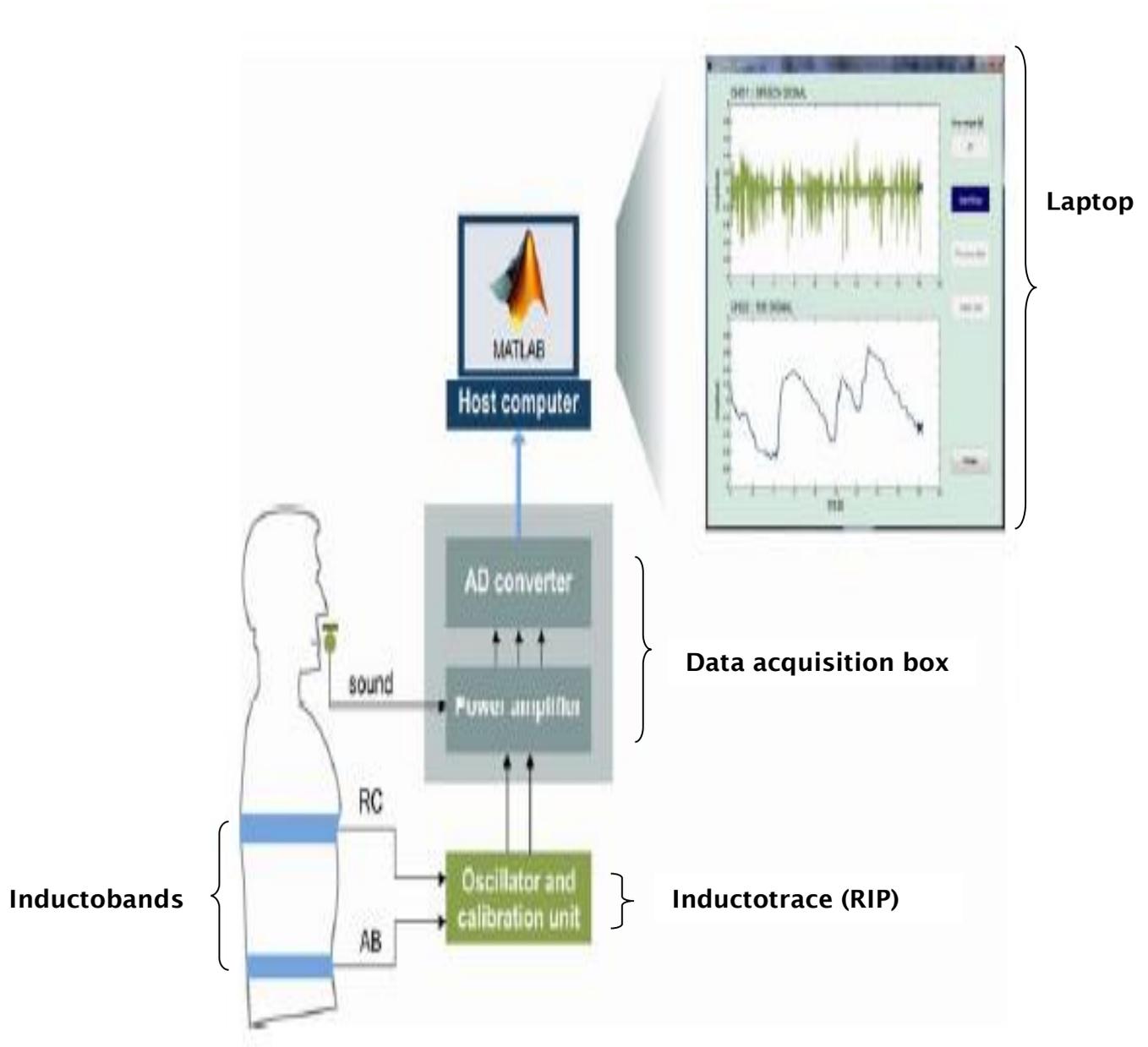


Figure 5 The equipment setup with reference to a) the placement of the Inductobands, and b) the connection between the calibration unit (the Inductotrace), data acquisition box and laptop computer

6.1.6 Research protocol

The same protocol was used to record breathing and speech breathing patterns for all three studies. Upon arrival, written informed consent was obtained from each participant (appendix 4). Basic demographic data were then recorded using a short questionnaire about age, sex and general health (appendix 5).

Equipment set up procedure

Participants were asked to remove clothing from the upper body (or undress to minimal undergarments) in order to allow the Inductoband belts to be applied close to the skin. They were given the opportunity to wear garments over the bands if they wished to be covered. To determine the correct belt size to use, participants were seated in a rigid high back chair with feet on the ground, and the circumference of the ribcage (taken just below the axilla) together with the circumference of the abdomen (taken below the lowest vertebral rib), was measured with a standard tape measure. Once the Inductobands were secured in place with a Velcro fastening, both Inductobands were connected to the RIP system via the transducer oscillator, and then into the corresponding input channel (RC and AB) of the custom-built A/D converter. A headset microphone was placed in front of the participant's mouth and amplified through an analogue amplifier, which was integral to the A/D converter.

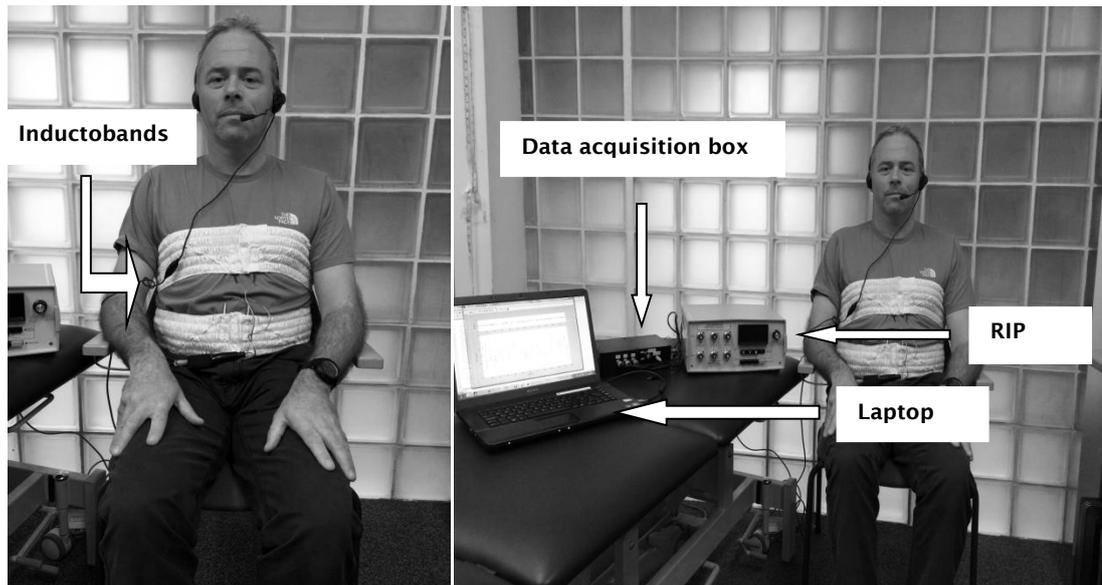


Figure 6 Example of a) the placement of the Inductobands, and b) the equipment set up, including the Inductotrace (RIP), data acquisition box and laptop. (NB; the model in this example is wearing upper body clothing for dignity purposes. In the privacy of the data collection sessions, the Inductobands were placed directly over the bare chest)

Speech tasks

Following the application of the RIP Inductobands and the head-set microphone, each participant was asked to complete a number of tasks. Breathing and speech breathing patterns were collected during four tasks; quiet breathing, reading, describing, and conversational speech. The speech tasks were selected for their ability to reflect different types of ‘constrained’ (reading) and ‘unconstrained’ speech (describing and conversation). Traditionally, speech breathing studies have examined the characteristics of speech breathing patterns according to age (Hoit & Hixon 1987; Hoit et al. 1990), body shape (Hoit & Hixon 1986) and sex (Hoit et al. 1989) for exploratory purposes. However, since speech breathing pattern analysis has yet to be considered for its potential as monitor of respiratory health, the type of speech that provides the most useful information during the analysis of speech breathing patterns has yet to be identified.

Breathing and speech breathing patterns were recorded during each task for a period of four minutes. There is no consensus within the literature regarding the optimal length of speech breathing patterns required to provide meaningful data. The majority of speech breathing research has so far based analysis of speech breathing patterns on relatively short recording periods, sometimes lasting as few as five breaths, which roughly corresponds to a 20 second recording period (Hoit & Hixon 1986; Hoit et al. 1989). Since the stability of breathing and speech patterns remains unknown, a decision was made to select a period of four minutes in order to provide a balance between providing enough data for interpretation, and remaining acceptable for participants to speak continuously. A description of each speech task will now be provided.

The Reading task

A standard reading passage printed on A4 paper in 'Times new roman' font (size 12) was given to the participants (appendix 6). The passage was chosen because it was descriptive, and it was anticipated that this would produce speaking behaviours characteristic of reading, rather than spontaneous speech. Using the Flesch readability tool in Microsoft Word 2010, the passage was given a Flesch score of 88. This meant that the passage had an 'easy' reading level and it was hoped that this would encourage participants to read without difficulty, as previous evidence suggests that speech breathing patterns are influenced by cognitive demand (Mitchell et al. 1996).

The Describing task

Participants were provided with the 4 different pictures depicting Greek art (appendix 7), and invited to describe the material, commenting on what they could see, the colours used and position of characters.

The Conversational speech task

Participants were encouraged to engage in continuous speech by responding to a series of 'open' questions or statements designed to prompt spontaneous speech, for example:

“Describe everything you did from the moment you woke up, until you returned back to bed yesterday”

If participants' seemed as if they were running out of topics to discuss, the researcher would ask another similar open ended question. Participants were told that the researcher would speak quietly when asking these questions to avoid the researcher's speech from being picked up on the microphone. After this task was complete, the researcher helped the participants to remove the Inductobands and they were able to get dressed before leaving. The sequence of events that was undertaken for each participant during the data collection session has been illustrated in figure 7.

Pilot work

Each of the three speech tasks were piloted (n=1) prior to the start of the first study. For the describing task, a willing volunteer agreed to describe a series of pictures for a period of four minutes in order to evaluate the usefulness of the describing material. During the pilot work, the volunteer was able to describe the images without any difficulties. The describing material consisted of four different pictures of Greek art. These pictures were selected for their 'dense' content, as each picture contained numerous characters, colours and objects that were positioned to signify a meaning. It was speculated that this choice of imagery would provide participants with ample visual material to encourage a continuous flow of spontaneous speech. The reading and conversational speech tasks were also performed satisfactorily.

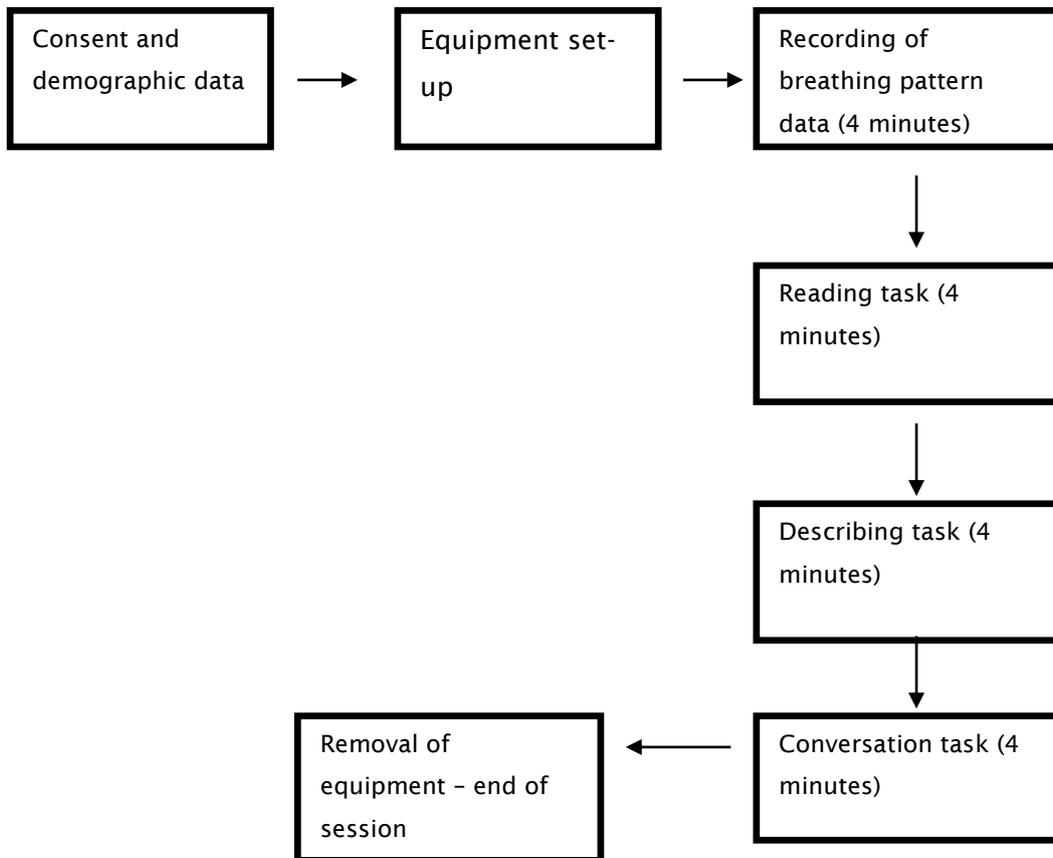


Figure 7 The order of the data collection procedure: sequence of events

6.1.7 Data extraction procedure

Breathing and speech breathing pattern data recorded by RIP during the various breathing and speech tasks were acquired using customised software to drive the Matlab (2009)[®] Data Acquisition Toolbox. Each raw data file was stored in Matlab format and was provided with an individual identification code for processing.

Using an algorithm developed by a postdoctoral research fellow from the Institute of Sound and Vibration Research (ISVR) (University of Southampton), breathing parameters relating to timing, magnitudes (a surrogate for volumes) and regional contributions of the ribcage and abdomen were identified using a semi-automatic process. A description of each breathing parameter that was examined in this research is provided in section 6.1.7.3, after the procedure used for extracting the parameters is firstly described.

6.1.7.1 Semi-automatic detection of breathing cycles

Breathing and speech breathing parameters were extracted from the raw data files using a peak detection algorithm written in Matlab®, which was used for all three studies. The methods employed for extracting breathing parameters from the raw data files from all three studies have therefore been exclusively described here to avoid repetition. In Matlab®, a typical trace containing the raw RIP and speech data can be seen in figure 8.

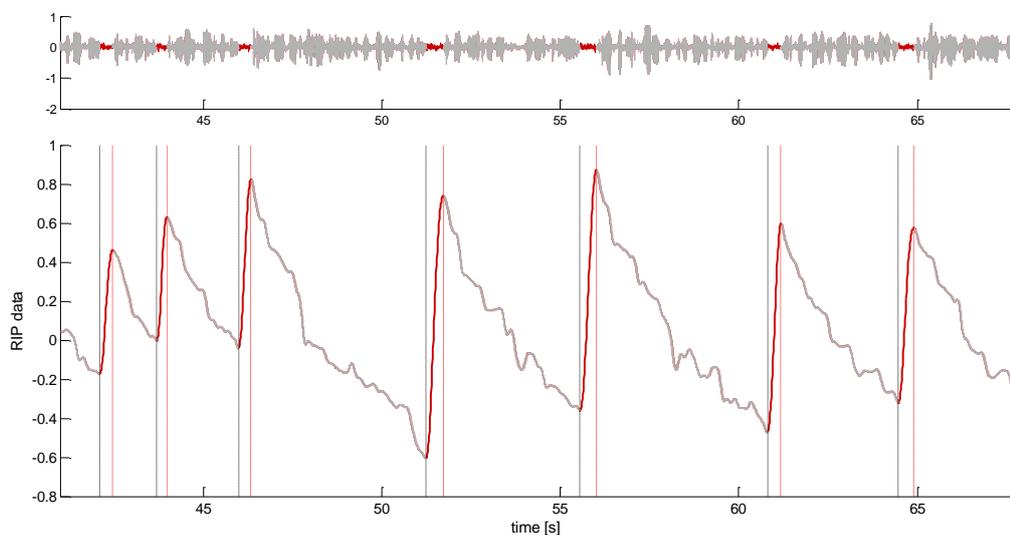


Figure 8 A typical trace from a speech breathing recording containing RIP (bottom graph) and speech (top graph) data in Matlab®

In figure 8, the bottom graph contains the breathing pattern data obtained by the RIP, while the top graph provides the corresponding speech data recorded by the head-set microphone.

Breathing parameters were calculated through the detection of the local minima and maxima of each **inspiration phase** throughout the entirety of each recording period. The minima and maxima were defined as the lowest and highest points respectively within a series of sequential short time-windows of the signal. These points were then used to detect the breathing cycles in each file. However, the automatically detected phases needed validation against the corresponding speech segment to ensure the exact determination of the two ends of each inspiration phase. As previously discussed in chapter five, speech

is principally produced in the expiratory phase of the breathing cycle (Hoit et al. 1989; Winkworth et al. 1995). Therefore, any segment of the RIP data which corresponded to speech (in the corresponding speech signal), belonged to the expiration phase. The algorithm sometimes incorrectly identified the start or end of an inspiration phase, due to local variations in the recorded signal. The incursion of speech into the inspiration phase was used as cue to identify and adjust manually for these misidentified locations. For each inspiration phase automatically detected by the algorithm, a decision was made either to: **keep, adjust/move, delete or add** the marker. Records have been kept for each of these decisions (Appendix 8), where the peak detection algorithm has been evaluated in section 8.8.1. A description of each of the adjustments will now be given:

*Example of when a decision was made to **keep** the marker for an inspiration phase*

Inspiration phases were kept if the corresponding speech segment was either silent (during inspiration) or when inspiratory sound could be heard (figure 9). This is because speech is predominantly produced during the expiration phase (Hixon 1973; Conrad & Schönle 1979).

How a period of ‘silence’ was defined

A period of silence was defined by the algorithm and the user. A method was implemented in the algorithm to estimate threshold values of two spectral features of the speech signal: short-time energy and spectral centroid. If the signal features were below the defined thresholds, the signal was designated as silent. Any algorithm-detected silence was validated by the researcher, as a period with no speech production.

*Example of a situation when a speech breathing file was **kept and not adjusted**:*

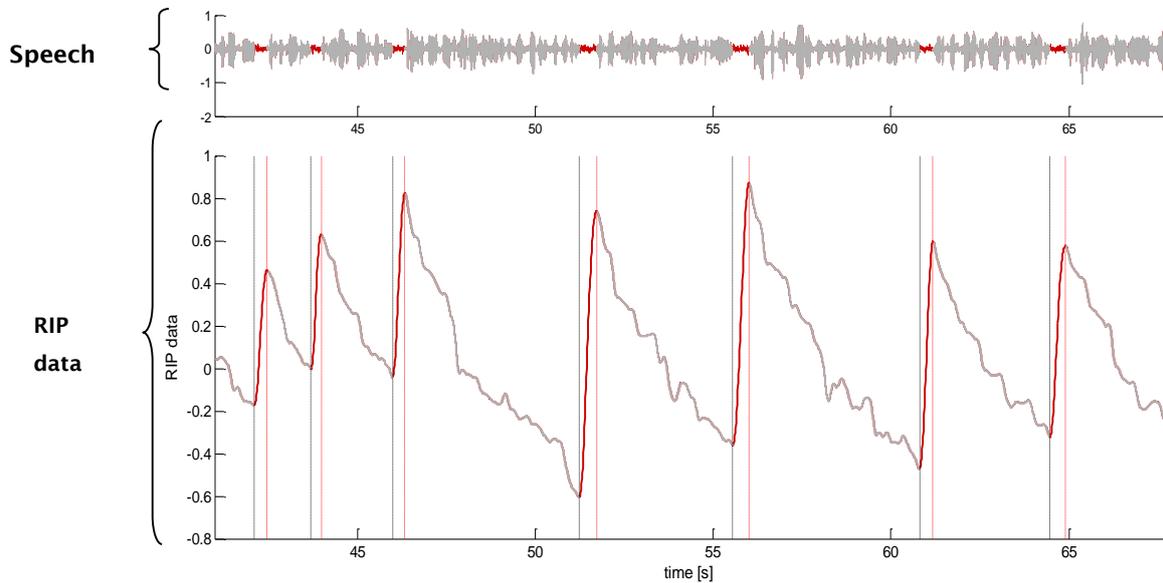


Figure 9 Example of a situation where the beginning and end of each inspiration phase **was kept**. Therefore **no** editing was required

Looking at the RIP data in the bottom graph of figure 9, each inspiration phase is highlighted in red; the dotted black line represents the beginning and the dotted red line represents the end of each inspiration phase. Based on the principle that speech is only produced during the expiration phase of the breathing cycles, figure 9 demonstrates that the corresponding speech signal for each inspiration phase is silent (the speech signal is flat). Since every inspiration phase in the RIP signal corresponded to a silent segment in the corresponding speech signal, no adjustments were made to the breathing cycles that were automatically detected.

Example of when a decision was made to **adjust** the marker for an inspiration phase.

The beginning and end of each inspiration phase was adjusted if the beginning and end of each inspiration phase did not match up with a period of silence in the corresponding speech signal (figure 10):

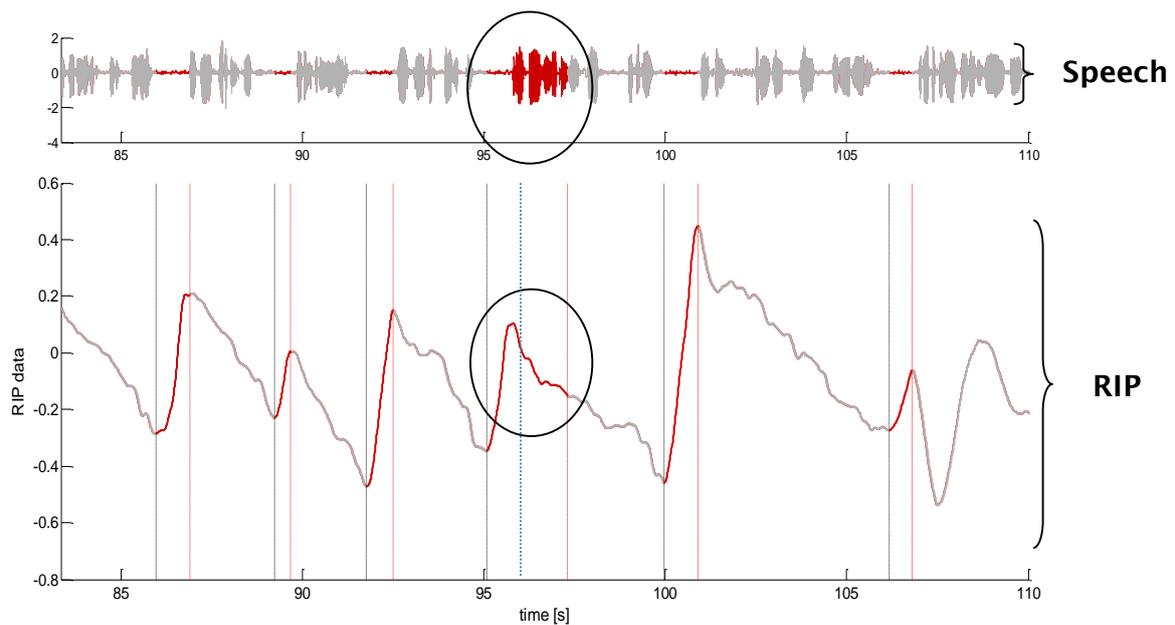


Figure 10 Example of where the end of an inspiration phase required manual **adjustment**.

Looking at the RIP data in the bottom graph (figure 10), the area highlighted by the circle demonstrates that the end of inspiration was incorrectly identified by the algorithm. The red dotted line (end of inspiration) exceeded the peak within the signal, and the corresponding speech signal was not silent. In this situation, the dotted red line marking the end of inspiration would be moved left, in line with the peak in the RIP signal and the end of the silence period in the corresponding speech signal. This new adjustment has been indicated by the blue dotted line.

*Example of when a decision was made to **delete** the marker for an inspiration phase.*

Inspirations were deleted if the algorithm wrongly identified the location of an inspiration phase within the expiration phase, which corresponded to a segment of speech (figure 11):

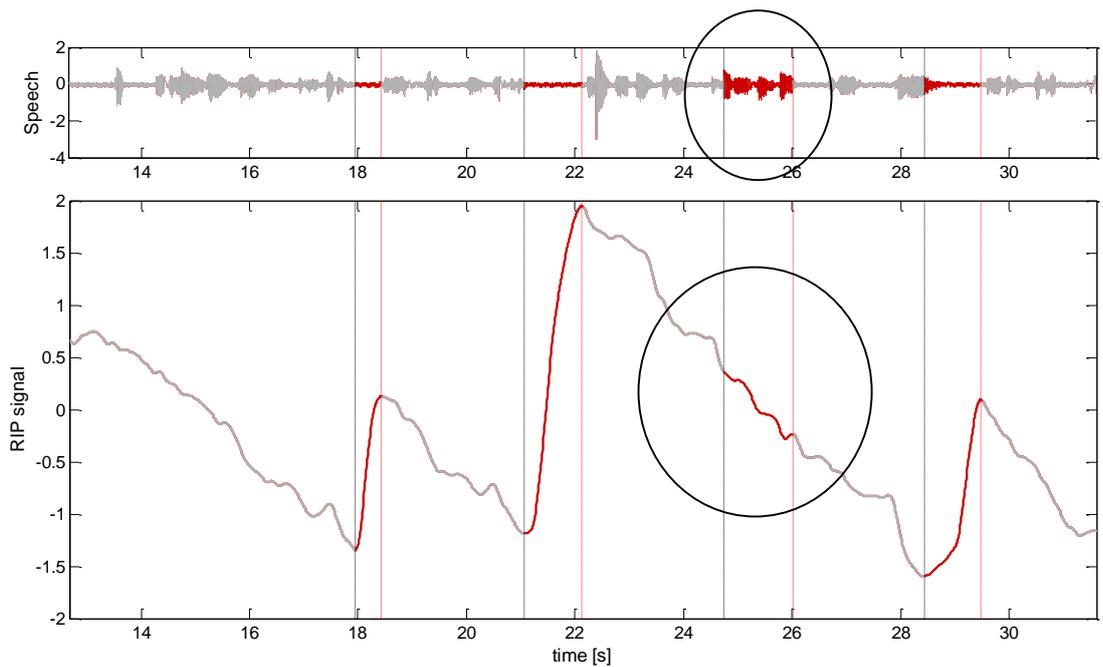


Figure 11 Example of an inspiration phase that needed to be **deleted**

Looking at the bottom graph in figure 11, it can be seen that the algorithm identified an inspiration phase even though a) there is no peak in the signal, and b) the corresponding speech signal (top graph) contains speech. In this case, both markers (marking the beginning and end of inspiration) would be deleted.

*Example of when a decision was made to **add** the marker for an inspiration phase.*

Inspiration phases were added/ marked when the algorithm did not detect the inspiration phase (figure 12):

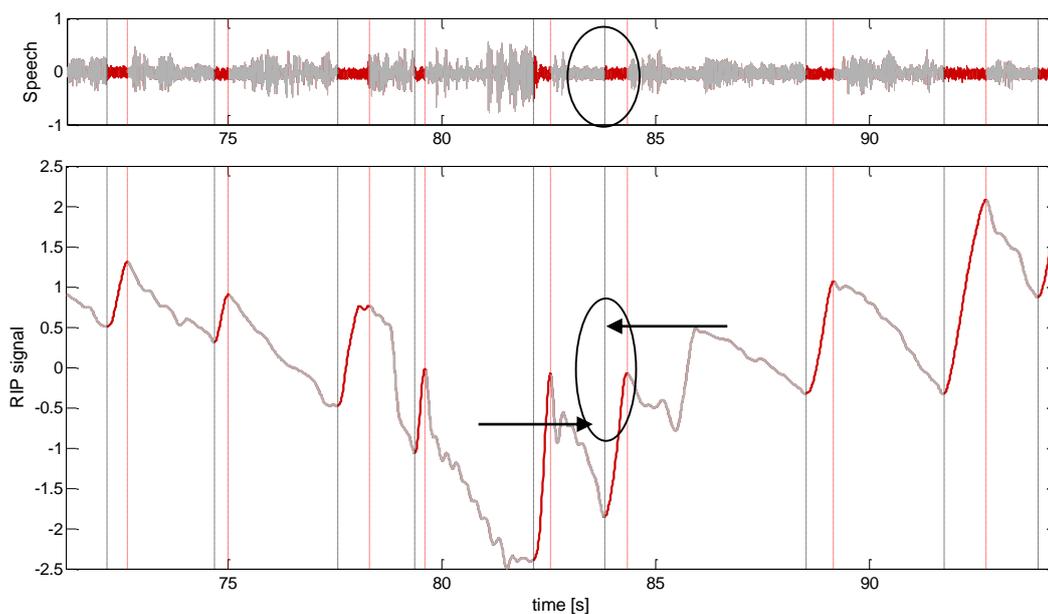


Figure 12 Example of a situation when an inspiration phase needed to be added.

Looking at the speech signal in the top graph in figure 12, it can be seen that the circle highlights a period of silence. However, a corresponding inspiration phase was not identified on the bottom graph with the RIP signal. In this case, the beginning and end of inspiration had to be added at the locations indicated by the arrows.

After each four minute speech breathing file was manually inspected and adjusted, the algorithm automatically calculated the mean value for each breathing parameter extracted over the four minute recording period. These data were then manually transferred into a SPSS spreadsheet (version 19).

6.1.7.2 Adjustment of data files

A record of the number of manual adjustments that were made for each of the raw data files (based on the choice to 'delete', 'add' or 'adjust/move') has been included in appendix 8. A total of 530 files were processed throughout the three data collection phases using the same peak detection algorithm. A discussion regarding the number of adjustments that were made in relation to the sample of participants has been provided in section 8.8.1.

6.1.7.3 Parameters of breathing pattern – definitions

Ten breathing parameters were extracted from the raw data file (Figure 13). These were: inspiration time (T_I) (in seconds), expiration time (T_E) (in seconds), inspiration magnitude (IM) (arbitrary units of volume), expiration magnitude (EM) (arbitrary units of volume), breathing cycle duration (T_{tot}) (in seconds), respiratory rate (RR) (breaths per minute), percentage contribution of the ribcage to inspiration (%RC Insp), percentage contribution of the abdomen to inspiration (%AB Insp), percentage contribution of the ribcage to expiration (%RC Exp) and the percentage contribution of the abdomen to expiration (%AB Exp). A definition of each breathing parameter will now be provided.

Respiratory timings and magnitudes

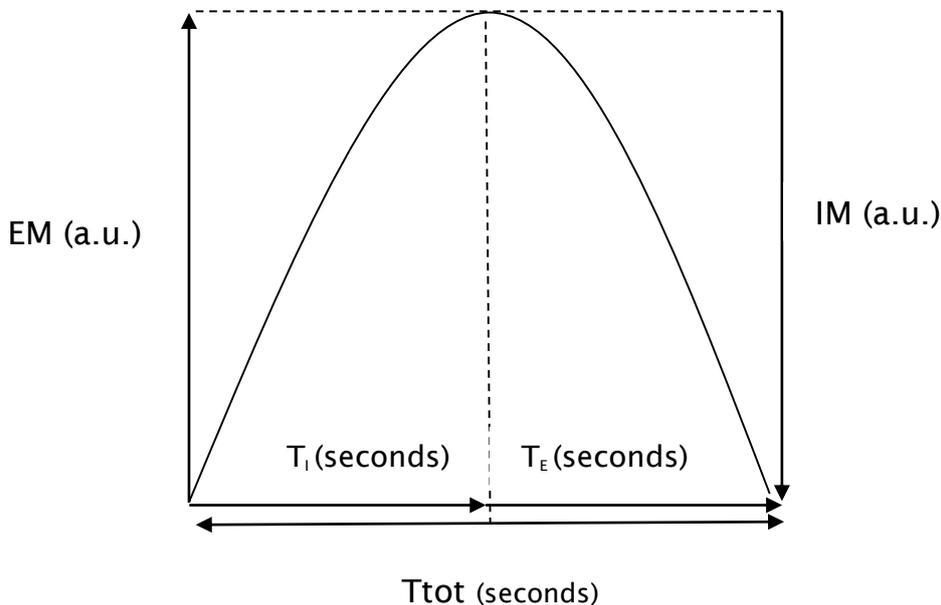


Figure 13 Schematic representation of the respiratory parameters extracted from one breathing cycle

Timing parameters:

1. **Inspiration time (T_i):** The process of actively drawing air into the lungs is defined as inspiration. Inspiration time was measured as the time in seconds between the beginning and end of the inspiration phase as indicated by silence in the speech signal and an upward slope left to right in the RIP signal.
2. **Expiration time (T_e):** Expiration is normally a passive process where air leaves the lungs (but can be active during pathology (Hough 2001)). Expiration time was defined as the time from the end of inspiration to the beginning of inspiration of the next cycle measured in seconds.
3. **Breathing cycle duration (T_{tot}):** The time it takes to complete a breathing cycle, calculated as $T_i + T_e$ measured in seconds.

N.B. In many breathing cycles individuals pause at the end of either inspiration or expiration. A full cycle thus comprises: T_i plus T_e plus any pauses.

The RIP and the speech signal are not able to detect or quantify such pauses and therefore throughout this research T_{tot} is simply T_i plus T_e and any pauses are included as part of T_i .

4. **Respiratory rate (RR):** was defined as the number of complete breath cycles per minute (bpm).

Volume parameters:

5. **Inspiration magnitude (IM):** was defined as the vertical distance between the minimum and maximum of each inspiration phase, and was proportional to the inspiratory volume.
6. **Expiration magnitude (EM)** was defined as the vertical distance between the maximum and minimum of each expiration phase, and was proportional to the expiratory volume.

NB: The units of the RIP signals for inspiration and expiration magnitude are arbitrary, because calibration was not performed against a spirometer or pneumotachograph. This means that they are proportional to inspiratory and expiratory volume, but do not have specific dimensions such as millilitres. See section 2.3.9 for more details.

Regional contributions of the ribcage and abdomen:

7. **Percentage contribution of the ribcage to inspiration (%RC Insp)** was defined as the proportion of total IM attributable to the rib cage band during the inspiratory phase
8. **Percentage contribution of the abdomen to inspiration (% AB Insp)** was defined as the proportion of total IM attributable to the abdominal band during the inspiration phase
9. **Percentage contribution of the ribcage to expiration (% RC Exp)** was defined as the proportion of total EM attributable to the ribcage band during the expiratory phase

10. Percentage contribution of the abdomen to expiration (% AB Exp) was defined as the proportion of total EM attributable to the abdominal band during the expiratory phase

6.1.8 Research Governance

6.1.8.1 Ethical considerations

Data obtained during all studies had ethical approval and sponsorship prior to participant recruitment. The first two studies were reviewed by a University of Southampton Ethical committee, and the third study was reviewed by a NHS Ethical committee. All protocols were subjected to Peer Review prior to submission. The first two studies were reviewed by the Faculty of Health Sciences ethics committee at the University of Southampton. Full ethical approval was granted by them for study one and two (see appendix 9) (FoHS - 2011038 (study one) and FoHS ID12246 (study two)). Indemnity insurance was then sought (appendix 10). Study three was approved by an NHS Ethical committee (REC reference: 12/SC/0302) (appendix 17).

6.1.8.2 Data protection and confidentiality

Data obtained during all three studies were used by the researcher and supervisors for the purpose of each study. Data relating to breathing patterns and speech were directly stored onto files on a laptop computer that was password secured, and data for each participant were allocated individual codes to ensure anonymity. All paper documentation including signed consent forms and demographic data were securely stored in a locked filing cabinet within the university, in compliance with the University of Southampton policy for postgraduate research.

6.1.8.3 Health and safety for the first two studies

The data collection procedure took place in a well ventilated, private room at the University of Southampton. A risk assessment was conducted prior to data collection procedure, where no hazards were identified, and all equipment was used in line with the manufacturer's safety standards. All Inductobands used

for recording were washed in accordance with the manufacturer's instructions, and the head set microphone was disinfected after every participant.

6.2 Study two

Breathing and speech breathing patterns in healthy 'older' adults

The protocol used for obtaining breathing and speech breathing pattern data from healthy older adults used the same protocol described for study one, with three minor changes: 1) the replacement of the 'describing task' with a counting task, 2) the duration of the speech breathing recordings was reduced to a two minute period and 3) the age of participants. In order to avoid repetition, a number of sections will refer back to appropriate sections in study one. Reasons for these changes are provided under section 7.2.1.

6.2.1 Design

A cross sectional design was used to obtain breathing and speech breathing patterns.

6.2.2 Participant selection

A decision was made to collect breathing and speech breathing pattern data from a sample of healthy 'older adults' so that a) the characteristics of speech breathing patterns could be characterised and explored within an older age group, b) the influence of age on breathing and speech breathing patterns could be examined, because there are unsubstantiated observations regarding changes in respiratory mechanics associated with increasing age (Janssens et al. 1999; Pride 2005; Watsford et al. 2007), and c) a comparative analysis could be performed between healthy older adults and participants with chronic respiratory disease in the absence of age as a confounder. To obtain a group to match against patients with chronic respiratory disease, a decision was made to include anyone between the age of 50 and 85 years with no history of chronic respiratory disease.

6.2.3 Recruitment procedure

The same procedure was used to recruit healthy older adults, as for study one. The exception to this description was that the age range sought was between 50 and 85 years.

6.2.4 Sample size

Although the data from the first study could potentially have been used to produce a power calculation for the second study, it was felt that there were still insufficient data regarding anticipated effect size to generate power calculations. In addition, the age range for the second study was different, so it was uncertain if calculations using data from the first study would be appropriate. A convenience sample of 20 participants was recruited for the second study. The sample sizes calculated for the retrospective power calculations have been provided in the discussion.

6.2.5 Equipment and set-up procedure

Breathing and speech breathing patterns were recorded simultaneously using the RIP and a head-set microphone. The equipment and set-procedure was as described in section 6.1.5.

6.2.6 Research protocol

Breathing and speech breathing patterns were obtained using the same research protocol that was describe for study one, with the exception of **two changes**. These changes were also included in the protocol used for obtaining data from study three:

1. The length of each breathing and speech breathing pattern data file was reduced to a two minute recording period.
2. The describing task that was used during study one was replaced with a counting task.

Justification for reducing the length of the recording period to two minutes

Following the observation that speech breathing patterns remained stable throughout the four minute recording period (see section 8.1.2), a decision was made to reduce the recording period used in the second and third studies to two minutes. The stability of breathing pattern data over four minutes in the first study suggested that a period of two minutes would be sufficient. In addition to improving the efficiency of the measurement protocol, reducing the recording period for each task would make the procedure more comfortable for the participants with chronic respiratory disease to complete (in study three). It was hoped that using a shorter speech recording period would reduce any need for resting and pausing during the recordings due to speaking related breathlessness (Lee et al. 1998; Hoit et al. 2007), as this would limit the quality of the data and would not provide a true representation of speech breathing patterns. Furthermore, the future goal for this research was to explore the possibility of using speech breathing pattern analysis as a respiratory monitoring tool, and demonstration of its ability to detect changes in respiratory health using short recordings would be advantageous for practical reasons.

Justification for the removal of the describing task and replacement with a counting task

It was observed during the first study that a number of participants found the 'describing' task challenging to complete. Although the task was originally designed to prompt spontaneous speech by encouraging participants to describe a number of images that were given to them, on a number of occasions, participants were unable to describe the picture, and often required prompting by the researcher, which caused them to pause frequently. In theory, it is possible that the task could have been made more simple for participants to complete by replacing the images with a more 'accessible choice, however it was speculated that this may have the opposite effect, limiting the richness of the description that participants could achieve (See section 8.1.1). A decision was therefore made to remove the describing task used in study one and replace it with a counting task. A counting task has been

previously used by other researchers to compare speech breathing patterns between health and disease. They reported that counting allowed them to identify the differences between health and disease because it increased respiratory demand (Loudon et al. 1988; Lee et al. 1993). A description of the counting task will now be given.

Counting task

Participants were asked to count from one to 120, keeping to a pace of one count per second by looking at a timer on a screen which set the pace for the task. If participants were unable to keep to this pace (if they became breathless for example), participants were advised to rest, or continue with a pace that was comfortable for them to complete within the two minute time frame.

6.2.7 Data extraction

Breathing parameters were estimated from the raw data files using the same data extraction methods described in section 6.3.11.

6.3 Study three

Breathing and speech breathing patterns in patients with chronic respiratory disease before, during and after a six week Pulmonary Rehabilitation programme.

6.3.1 Design

This third study was set up as an observational, repeated measures design to obtain some breathing/speech breathing pattern data before, during and after PR from patients with COPD and bronchiectasis. Speech breathing patterns were obtained from each participant at three specific time points, that is, the first, middle and last day of PR.

The primary interest was in whether speech breathing patterns were responsive to an intervention. It has been acknowledged that in order to provide a definitive answer to any question about whether PR changes speech breathing

patterns, a study would need an experimental design with a control group (Kendall 2003; Stanley 2007). Patients with chronic respiratory disease would need to be randomised into one of two groups; one active group receiving PR, and one control group without PR. Baseline measurements could be taken before randomisation, and then at various time points, where the primary comparison would be between the 'control' and 'active' groups at the final outcome. In keeping with an experimental RCT, the PR intervention would also need to be standardised to maintain consistency throughout the trial and to ensure that every participant received the same treatment. Setting up an RCT of this kind was beyond the financial and practical scope of this PhD. This was primarily because of the financial cost associated with setting up and delivering an 'independent' PR intervention for the purpose of a trial.

Instead, the researcher made use of an existing clinical intervention with a sound evidence base for effectiveness, to provide some proof of principle before and after PR data. Currently there is no published literature documenting speech breathing patterns before and after any clinical intervention, and no previous work on responsiveness of speech breathing patterns.

6.3.2 Participant selection and setting

Patients with respiratory disorders who had been enrolled onto the PR programme at St. Richard's Hospital NHS Foundation Trust (Chichester) were eligible to participate in the study. Data collection took place within a clinical room at St. Richard's Hospital.

6.3.3 Inclusion criteria

Any patient who had been enrolled on to the PR programme with a restrictive, obstructive or other relevant clinical diagnosis was eligible for inclusion in the study. Patients were invited to attend PR by the respiratory physiotherapist if they fulfilled the following criteria (St. Richard's Hospital clinical criteria):

- Decreased exercise tolerance
- Symptomatic, stable chronic lung disease

- Cardiovascularly stable
- Blood pressure no greater than 170/100 but ideally less than 150/90
- Heart rate stable; no untreated arrhythmias or new tachycardia
- Breathlessness of pulmonary origin
- Good motivation - assessed by asking the patient whether they would like to participate in PR.
- Medically stable
- Know this is a group activity which requires regular attendance
- Stable co-morbidities
- Optimal medication - During PR assessment, patient medication was reviewed by the respiratory nurse to ensure that patients were taking the optimal medication for respiratory symptom control.

6.3.4 Exclusion Criteria

Patients were excluded from the study if they had any contraindications to attending PR. The following conditions were considered as absolute contraindications to attending PR (St. Richard's Hospital clinical criteria):

- Uncontrolled asthma
- Cancer of poor prognosis
- Active pulmonary TB
- Unstable angina
- Uncontrolled diabetes
- Uncontrolled hypertension (Blood pressure >170/100)
- Dangerous cardiac arrhythmias
- Recent cardiac event (such as myocardial infarction within 6 weeks)
- Poor motivation
- Severe cognitive impairment (such as Dementia)
- Any serious condition which would prevent exercise or be exacerbated by exercise

6.3.5 Participant recruitment

Potential participants were identified from the PR assessment clinic at St. Richard's Hospital (Chichester). Patients with a diagnosis of chronic respiratory

disease were referred to these clinics by their GPs to assess their suitability for attending PR. Agreement was given by the respiratory specialist nurse and physiotherapist to hand out a study information pack to each patient who was enrolled onto a PR programme during the assessment clinics. Each information pack contained a patient invitation letter (appendix 11), Participant Information Sheet (PIS) (appendix 12), reply slip (appendix 13) and a pre-paid and pre-addressed envelope. If interested, patients were advised to fill in the short reply-slip with their name and convenient contact number, and post using the pre-paid envelope. Once the reply slip was received by the researcher, each patient was contacted via telephone to a) confirm whether they still wished to participate in the study, and if so b) to organise the dates for data collection. After every telephone call, a formal confirmation letter was sent to each participant (appendix 14), and then a final confirmation letter was sent nearer the time confirming the dates and times of each of the three data collection sessions (Appendix 15). A flow diagram modelled on CONSORT recommendations (Moher et al. 2001; Tooth et al. 2005) for reporting results from an observational study has been developed in order to clarify the numerical history of the pre and post PR study (figure 14).

Flow diagram to clarify participation

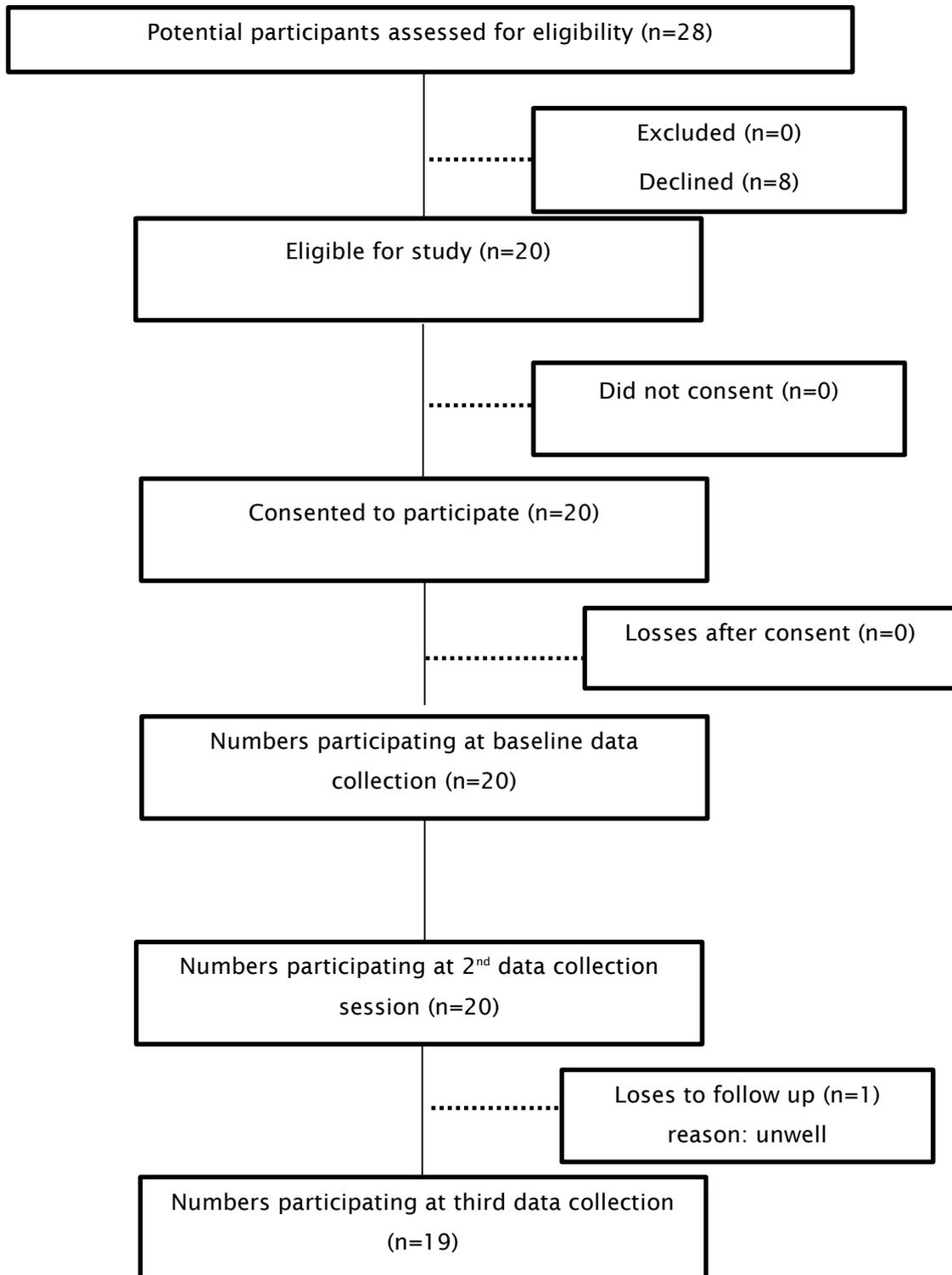


Figure 14 Participation flow diagram modelled on CONSORT recommendations (Moher et al. 2001)

6.3.6 Sample size

This was an exploratory observational study which aimed to determine if and how speech breathing patterns changed in patients with chronic respiratory disease following a six week PR programme. The use of power calculations were deemed inappropriate, as the intention was to explore attributes of speech breathing rather than to test a statistical hypothesis. The proposed study was to be the first to examine speech breathing patterns over time following a therapeutic intervention in patients with chronic respiratory disease. Therefore, it was decided to recruit a convenience sample of 20 patients with chronic respiratory disease. Retrospective power calculations were performed in order to determine the sample size needed for future studies based on findings from the current research. These have been discussed in chapter eight and can be found in appendix 3.

6.3.7 Equipment and set up procedure

The same equipment and set up procedure that was used in the first two studies, was also used in the third study where breathing and speech breathing patterns were recorded using RIP. Please refer back to section 6.1.5 for specific details regarding the equipment and set up procedures.

6.3.8 Research protocol

During study three, breathing and speech breathing pattern were recorded during four two minute periods of quiet breathing, reading, counting and spontaneous speech from patients with COPD and bronchiectasis at three different time points; before, during and after a six week PR programme (figure 15).

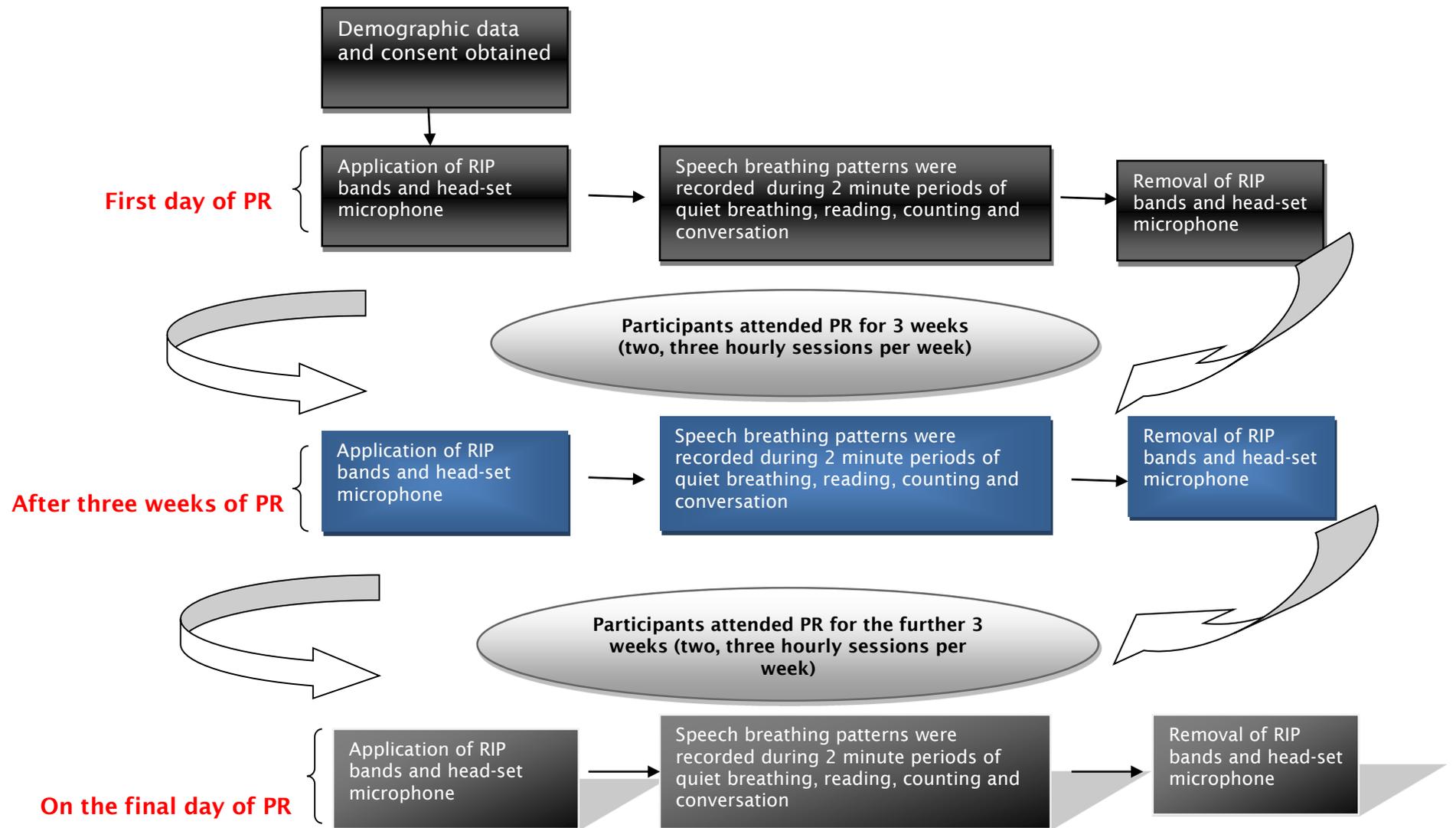


Figure 15 Data collection timeline used in third study: Sequence of events

6.3.9 Pulmonary Rehabilitation Programme

All participants were enrolled onto a six week PR programme which took place in the outpatients department at St. Richard's Hospital NHS Foundation Trust (Chichester). Patients attended two (three hourly) supervised sessions per week (every Tuesday and Thursday). PR consisted of a combination of supervised exercise training (one hour each session), education and behavioural adaptation strategies. These components have been described in chapter four. The researcher was not present during the PR sessions, as it was anticipated that this may have altered the behaviour of the participants attending PR.

6.3.10 Patient centred outcome measures

On this PR programme it was standard practice for patients' progress to be assessed via a series of clinical assessments at the baseline session, and then six weeks after, on the final day of PR, so that pre and post PR comparisons could be made. This information was recorded by the clinical respiratory physiotherapist, and the researcher subsequently obtained the assessment data from patients' medical notes. It was considered appropriate to examine data relating to breathlessness and functional exercise capacity because these measures were available in the medical records and have been shown to reflect the physiological changes associated with PR (Couser et al. 1995; Lacasse et al. 2007). The methods used to obtain data relating to exercise capacity and perceived breathlessness by the respiratory physiotherapist will now be described.

6.3.10.1 Functional Exercise capacity – Incremental Shuttle Walk Test (ISWT)

Exercise capacity was routinely assessed by the PR team using the incremental shuttle walk test (ISWT) at the beginning of the PR programme and then again after six weeks, on the final day of PR. The respiratory physiotherapist supervised this task, and the test data were retrieved from the patient medical notes by the researcher.

Participants were instructed to walk along a level 10 metre track at a previously determined speed, which was dictated by signals from an audio tape recorder.

The walking speed was progressively increased during one minute intervals, for a total of 12 stages. Participants were encouraged to continue through the stages by the respiratory physiotherapist. The test would cease when patients become too breathless or were unable to continue with the test at the dictated speed. The distance travelled in metres was calculated from the number of laps completed, where each lap consisted of 10 metres. Pre and post measurements of heart rate, oxygen saturation and breathlessness (Modified Borg Score – see section 7.6.2) scores were obtained and documented.

6.3.10.2 Measurement of breathlessness - Modified Borg Scale

Breathlessness was not the main outcome measure of interest in this research, however data relating to the perception of breathlessness were used as a possible surrogate for the effectiveness of PR. The Modified Borg Scale (appendix 16) is a well validated and widely used tool for measuring the subjective experience of breathlessness (Chen et al. 2002; Ries 2005), and was used to assess breathlessness at St. Richard's Hospital. Measurements of breathlessness were taken at four different time points throughout the PR programme; a) on the first day of PR, before the ISWT, b) on the first day on PR, after the ISWT, c) on the last day of PR, before the ISWT, and d) on the last day on PR, after the ISWT. The Modified Borg Scale consisted of a 10 point scale. Each point was anchored to a description of breathlessness starting from 0 (nothing at all), to 10 (shortness of breath so severe you need to stop). Participants rated their level of perceived breathlessness, and these data were recorded in their medical notes.

6.3.10.3 Physiological measurements (Oxygen saturation and heart rate)

Physiological measurements (oxygen saturation (SpO₂) and heart rate (HR)) were also routinely measured by the respiratory physiotherapist alongside Modified Borg Scores at the same time points, on the first and last day of PR. These data were also recorded in the medical notes by the respiratory physiotherapist, and later retrieved by the researcher.

Saturation of oxygen and HR were recorded using pulse oximetry. Most pulse oximeters have an absolute mean error of $\pm 2\%$ (Stoneham et al. 1994). These

measurements were obtained by placing an oximeter probe on the index finger of the participant.

Data relating to lung function (FEV_1 , FEV_1 % predicted, and FEV_1/FVC ratio) were retrieved from the medical notes. However, spirometry tests were conducted during the PR assessment clinics. These took place up to three months prior to the beginning of PR depending on patient availability, and a number of patients had these data missing from their notes (section 7.4.3). Lung function was only documented at the pre PR assessment clinics; lung function testing was not carried out by the respiratory physiotherapist following PR, so these data were not available for comparison.

6.3.11 Data extraction procedure

Ten breathing parameters relating to respiratory timings, magnitudes (volumes) and the regional contributions of the rib cage and abdomen (outlined in section 6.1.7.3) were extracted from the raw data files using the same peak detection algorithm described in section 6.1.7.

6.3.12 Research governance

6.3.12.1 Ethical consideration

As previously described, the third study was approved by an NHS ethics committee (Southampton Central (A)) (appendix 17), because the study recruited patients from an NHS hospital (Ethics number: 12/SC/0302). Research and development (R&D) approval was also granted from St. Richard's Hospital NHS Foundation Trust (Chichester) (R&D reference: 1498/NOC1/2012) (appendix 18).

6.3.12.2 Data protection and confidentiality

The same data protection and confidentiality procedures were adhered to as outlined in the first two studies. Please refer to section 6.1.8 for more details.

6.3.12.3 Health and safety

The data collection procedure was conducted within a well ventilated room at St. Richard's Hospital, Chichester. Although the cohort of participants included a patient group, these patients were considered to be physiologically stable, as they were attending PR on an outpatient basis. However, in case of any emergency, the room was equipped with an emergency alarm. When initiated, this alarm would notify acute medical staff to a medical emergency. However, an adverse event did not occur at any point during the data collection process.

6.4 Plan for statistical analysis

Two types of data were obtained from the three studies that were conducted in this research; 1) data obtained directly by the researcher (breathing/speech breathing patterns) and 2) data which were retrieved from the medical notes by the researcher (Modified Borg Scores, ISWT test results and physiological measurements). The latter was only obtained in the third study from participants with COPD and bronchiectasis. The ten breathing and speech breathing parameters that were extracted from the raw data files from each of the three studies were subsequently analysed and are presented in six sections (chapter seven). The statistical significance level was chosen as 95% and thus a result was considered as statistically significant if $p < 0.05$. An outline of the statistical tests that were used will now be given.

6.4.1 Analysis of demographic and anthropometric data

Data relating to age, sex and lung function (COPD and bronchiectasis data) were entered into SPSS (version 19), where descriptive statistics (mean and standard deviation) were generated to characterise the sample.

6.4.2 Breathing pattern characteristics and comparison between tasks in healthy younger adults, healthy older adults, adults with self-reported asthma and patients with chronic respiratory disease (COPD and bronchiectasis)

In SPSS, the group mean and standard deviation were calculated for each breathing parameter and task. After testing for normal distribution using the Shapiro-Wilk tests, individual breathing parameters were compared between

each of the breathing and speech tasks using a one way repeated measures ANOVA. Any significant differences that were identified by the one-way ANOVA were subsequently followed up by post hoc t-tests adjusted via a Bonferroni correction for multiple comparisons. A justification for the selection of this post hoc test has been provided in section 7.1.5. This analysis was performed for the data obtained from all data sets (healthy adults, healthy older adults, adults with self-reported asthma, patients with COPD and bronchiectasis and pooled patients with COPD and bronchiectasis).

6.4.3 Breathing pattern variability

The co-efficient of variation (CoV) was used to examine speech breathing variability. This was defined as the ratio of the standard deviation to the mean (expressed as a percentage), calculated by $(SD/Mean) \times 100$. The CoV% was calculated for each breathing parameter during each speech task for the group. The advantage of using this CoV% is that it is dimensionless, enabling comparisons to be made between different data sets.

6.4.4 Analysis of the stability of the data in healthy younger adults

The duration used to record breathing/speech breathing patterns has varied considerably in the literature, and it is currently unknown whether breathing patterns remain stable throughout these time periods. Demonstration of their ability to remain stable during shorter recordings could improve the efficiency of protocols used to measure breathing/speech breathing patterns, while still providing meaningful data. Breathing parameters were therefore characterised for every one minute interval throughout a four minute recording. Cumulative times were also calculated (ie, 0-2 minutes, 0-3 minutes and 0-4 minutes). After testing for normal distribution using the Shapiro-Wilk test, a one way repeated measures ANOVA was used to test for any statistically significant differences between each time point.

6.4.5 Examination of the influence of age and sex on breathing and speech breathing parameters in healthy adults

The influence of age and sex on each breathing and speech breathing parameter was examined from the pooled healthy data from the first two studies (healthy adults and healthy older adults) using multiple linear regression. Regression analysis was chosen for its ability to provide information about whether age and sex had any significant influence on each parameter, as well as its ability to provide detail about the relationship between age and sex on each outcome. That is, the model provided additional information about the predicted change in the expected value in the outcome when the independent variable is increased by one unit.

6.4.6 Comparative analyses

A comparative analysis was performed using independent t-tests between the following groups of participants:

1. Healthy young adults *versus* healthy older adults
2. Healthy young adults *versus* young adults with self-reported asthma
3. COPD patients *versus* bronchiectasis patients
4. Healthy older adults *versus* pooled patients with COPD and bronchiectasis

Since a) a number of interdependencies were present among the breathing pattern data, and b) multiple t tests were being performed, a decision was made to reduce the number of breathing pattern parameters that were included during the comparison analysis in order to reduce the probability of type one errors. A decision was made to base the comparative analysis on four breathing parameters: Expiration time, expiration magnitude, respiratory rate and the regional contribution of the ribcage to expiration (%RCExp). A justification for the selection of these parameters has been provided in section 7.5.2. All comparative analyses were performed using independent t tests adjusted via Bonferroni corrections.

6.4.7 Pulmonary Rehabilitation data

Two types of data were obtained from the third study; a) researcher collected data relating to breathing/speech breathing patterns which were obtained by the researcher from each participant, and b) clinical PR outcome data, which were routinely collected and retrieved from the patients' medical notes by the researcher. Although the detailed analysis of breathing/speech breathing parameters was the principal measure of interest in this study, it was considered appropriate to analyse the available clinical PR data (breathlessness and exercise capacity) before and after the programme, as these factors might reflect whether or not physiological changes occurred following PR. The following sections will therefore consider the analysis plan for the clinical data (breathlessness and exercise capacity) and breathing/speech breathing pattern data respectively.

6.4.8 Clinical data

6.4.8.1 Exercise capacity (ISWT)

The mean distance travelled (in metres) during the ISWT by the group was calculated, and a comparison was made between the baseline and post intervention measurement using a paired t test. Percentage difference between the baseline and post intervention measurement was also calculated by: $\text{difference between baseline and post intervention distance} / \text{baseline distance} \times 100$. Before and after PR exercise capacity was firstly examined for the group, and then individually during a descriptive analysis (looking at the actual distances travelled by each patient before and after PR).

6.4.8.2 Breathlessness data (Modified Borg Scores)

In total, each patient completed four Modified Borg Scale assessments, that is, before and after each shuttle walk test, both before and after PR. Breathlessness data were firstly compared at rest (pre shuttle) before and after PR assessment, using Wilcoxon's rank test for related samples, and then the post shuttle walk test data from before and after PR were compared.

6.4.8.3 Physiological measurements (HR and SpO₂)

Descriptive statistics (group mean and Standard Deviation) for oxygen saturation and heart rate (SpO₂ and HR) were calculated for all the group shuttle walk tests. Paired t tests were used to compare the values obtained from the shuttle walk tests before and after PR.

6.4.9 Comparison of breathing/speech breathing data before and after a six week PR programme.

The aim of study three was to determine if or how breathing/ speech breathing parameters altered over time following a routine therapeutic intervention (PR) with reported beneficial effects on breathlessness and exercise capacity (Lacasse et al. 2007; Ries et al. 2007). Each speech breathing parameter was compared between the three measurements taken before PR, after three weeks and then on the final day of PR using a one way repeated measures ANOVA.

6.5 Summary of chapter six

This chapter has presented a detailed description of the procedures used to collect and analyse breathing and speech breathing patterns during the three studies from 29 healthy adults, 20 healthy older adults, 11 adults with self-reported asthma, and 20 patients with chronic respiratory disease (14 COPD, 6 bronchiectasis) before, during and after they attended a six week PR programme.

Chapter Seven

Results

Introduction

The findings from the three data sets obtained during these studies are presented here in six sections. 1) In the first section which is headed **“Breathing and speech breathing patterns characterised in healthy young adults”**, breathing parameters have been characterised in healthy adults and examined for any differences between various breathing and speech tasks (quiet breathing, reading, conversation and describing). Breathing pattern variability and stability have also been examined across different recording periods. 2) In the second section which is headed; **“Breathing and speech breathing patterns characterised in healthy older adults”**, breathing and speech breathing patterns are characterised in healthy older adults and examined to see if any were ‘task specific’ within an older healthy population. 3) In section three **“The influence of age and sex on breathing and speech breathing patterns”**, the influence of age and sex on ‘healthy’ breathing patterns has been explored using pooled data from the healthy young and healthy older groups. 4) In the fourth section which is headed; **“Breathing and speech breathing patterns characterised in patients with chronic respiratory disease”**, breathing and speech breathing patterns have been characterised in adults with self-reported asthma, and in patients with a diagnosis of COPD or bronchiectasis. 5) In the fifth section which is headed **“Breathing and speech breathing patterns: comparisons between groups”**, breathing and speech breathing parameters have been compared between: a) Healthy young adults and healthy older adults; b) Healthy young adults and young adults with a self-reported history of asthma. c) Patients with COPD and patients with bronchiectasis, before pooling the COPD and bronchiectasis data into one group, of chronic respiratory disease (CRD). d) This CRD patient group has then been compared with the healthy older adult group. 6) In the sixth section, which is headed **“Breathing and speech breathing patterns before and after a six week Pulmonary Rehabilitation in patients with chronic respiratory disease”**, breathing and speech breathing patterns and variability are compared between the first and last day of a six week PR programme in patients with chronic respiratory disease (COPD and bronchiectasis). Clinical

outcomes have also been explored. A summary of all the analyses has been presented at the end of the chapter.

7.1 Section one

Breathing and speech breathing patterns in healthy young adults

In this section, breathing and speech breathing patterns have been explored in a sample of 29 healthy adults with no previous history of respiratory disease, to characterise speech breathing patterns in a sample healthy younger adults with no previous history of respiratory disease, to test the feasibility of the research protocol, and to optimise speech tasks and length. Demographic data have been presented first, before breathing and speech breathing parameters are characterised for the group, and compared among the breathing and speech tasks (quiet breathing, reading, spontaneous speech and describing). Breathing and speech breathing variability have then been presented followed by an examination of the stability of breathing parameters over different time periods.

7.1.1 Aims, research questions and hypotheses

Aims:

Data gathered from the first study aimed to explore the breathing and speech breathing patterns in a heterogeneous sample of 29 healthy adults with no previous history of chronic respiratory disease. The specific research aims were as follows:

1. To examine the feasibility of recording speech breathing patterns during different types of speech using a semi-automatic algorithm to extract breathing parameters from the raw data files.
2. To determine whether breathing and speech breathing parameters remained stable across a four minute recording period.
3. To characterise breathing/speech breathing patterns during quiet breathing and different types of speech (reading, describing and conversation).

4. To characterise breathing speech/breathing pattern variability in during quiet breathing and different types of speech (reading, describing and conversation).
5. To determine whether healthy younger adults produced 'task specific' breathing patterns during different speech tasks.

Research questions:

1. Is the detection of breathing cycles using a semi-automatic algorithm feasible for extracting breathing and speech breathing parameters from the raw data files?
2. Do healthy young adults produce 'task specific' breathing and speech breathing patterns during a quiet breathing, reading, describing speech and conversation task?
3. Do breathing and speech parameters remain stable throughout a four minute recording period in healthy adults during a quiet breathing, reading, describing and conversation task?

Hypotheses developed after data collection:

- HP1a** There is a statistically significant difference in respiratory timing parameters (inspiration and expiration time, breathing cycle time and respiratory rate) between a quiet breathing, reading, describing and conversation task in healthy young adults.
- HP1b** There is a statistically significant difference in respiratory magnitudes (inspiration and expiration magnitude) between a quiet breathing, reading, describing and conversation task in healthy young adults.
- HP1c** There is a statistically significant difference in the regional contributions of the rib cage and abdomen (%RCInsp, %ABInsp, %RCExp, %ABExp) between a quiet breathing, reading, describing and conversation task in healthy young adults.

7.1.2 Demographics

Forty adults were recruited into the study which set out to examine breathing and speech breathing parameters in a heterogeneous adult sample. Since there

is currently no definitive agreement as to what variables affect breathing patterns and speech breathing parameters (Hoit & Hixon 1987; Han et al. 1997), no specific exclusion criteria were defined for the study. Based on the known prevalence of self-reported asthma in a UK population (10-13%) (European Respiratory Society 2015), it was anticipated that some participants in the population would have a history of asthma, and it was hypothesised that they could provide useful information on speech breathing patterns in disease. In the event, 11 participants who reported a history of asthma were recruited into the sample. Data from these 11 have therefore been analysed and presented separately, see section 7.4.4. The sample of 29 healthy young adults (Males=12) had an average age of 33.7 ± 12.85 years. Data from 29 healthy young adults will now be presented

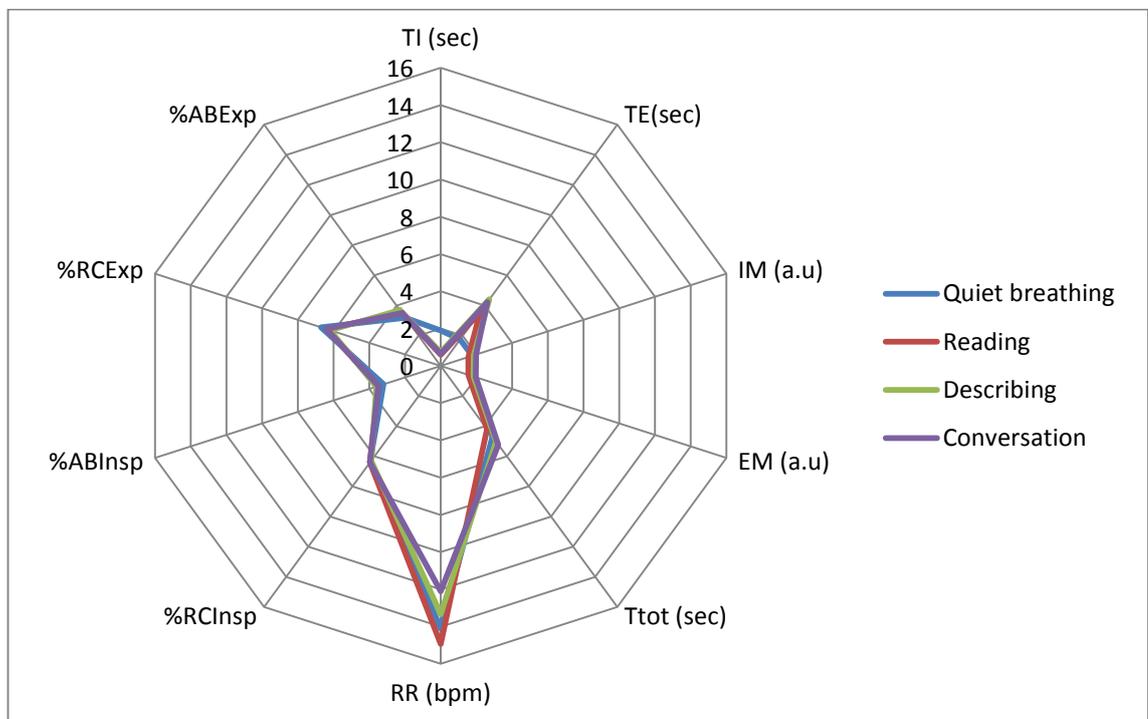
7.1.3 Breathing and speech breathing characteristics in 29 healthy adults during four minute periods of quiet breathing, reading, describing and conversational speech

Descriptive statistics (mean and standard deviation (SD)) were calculated for each breathing parameter during each four minute task (quiet breathing, reading, describing and conversation). Table 3 presents both the descriptive statistics for the group ($n=29$), and the results from the one way repeated measures ANOVA which tested for statistically significant differences between the tasks.

Looking firstly at the descriptive statistics (table 3), quiet breathing was clearly differentiated from the speech tasks by its respiratory timing components. On average, the quiet breathing task was associated with the longest inspiratory phase (nearly half of the respiratory cycle time), while the expiratory phase was comparatively shorter when compared to the speech tasks (reading, conversational speech and describing). Each speech task was characterised by having a short inspiratory phase, and long expiratory phase. Within the speech tasks, reading was associated with the shortest respiratory timing parameters (inspiratory, expiratory and total breathing cycle time), and the fastest respiratory rate. Breath sizes (inspiratory and expiratory magnitudes) were also found to be the smallest during the reading task, while the conversational speech task was associated with the largest magnitudes and longest respiratory timings. Consequently, the conversational speech task was associated with the slowest respiratory rate. When examining the percentage

ribcage and abdominal contributions to inspiration and expiration, these appeared to be similar across all tasks. On average, tidal breathing was dominated by ribcage displacement (around 64%), with minor differences between the tasks.

These data have been graphically illustrated in a radar chart (figure 16) in order to display the overall breathing pattern profiles during the various breathing and speech tasks. Each axis has been scaled according to seconds (inspiration, expiration and breathing cycle time), magnitudes (inspiration and expiration), breaths per minute (respiratory rate) and percentages (regional contributions of the ribcage and abdomen). The latter have been divided by ten, in order to scale the parameter in proportion to the other measures.



TI (sec) = Inspiration time (seconds); **TE (sec)** = expiration time (seconds); **IM (a.u)** = inspiration magnitude (arbitrary units); **EM (a.u)** = Expiration magnitude (arbitrary units); **Ttot (sec)** = breathing cycle time (seconds); **RR (bpm)** = respiratory rate (breaths per minute); **%RCInsp** = Ribcage percentage contribution to inspiration; **%ABInsp** = Abdominal percentage contribution to inspiration; **%RCExp** = Ribcage percentage contribution to expiration; **%ABExp** = Abdominal percentage contribution to expiration

Figure 16 Radar chart: Breathing pattern profiles in 29 healthy adults during the quiet breathing, reading, conversational speech and describing task

7.1.4 Analysis of variance between breathing and speech tasks

Each parameter was tested for statistically significant differences among the four tasks in order to determine whether breathing patterns were ‘task

specific'. After testing for normal distribution using the Shapiro-Wilk test, the data from each breathing parameter for any given task were found to be normally distributed. A decision was subsequently made to use an ANOVA with a repeated measures design to test for any statistically significant differences amongst the tasks, as the same group of participants completed all tasks. Table 3 presents the results from the one way repeated measures ANOVA according to each breathing parameter. The Greenhouse Geisser correction was used when the assumptions of Mauchly's Test of Sphericity were violated.

Based on the findings from the one way repeated measures ANOVA presented in table 3, statistically significant differences were found amongst the tasks for each breathing parameter, apart from the percentage abdominal contribution to inspiration ($F=2.14$, $df=3$, $p=0.09$).

Table 3 Breathing and speech breathing parameters during each four minute task in 29 healthy young adults: Descriptive statistics and results from the one way repeated measures ANOVA

n=29					Results of the one way ANOVA		
	Quiet breathing	Reading	Conversation	Describing	F	df	p
T _i (sec)	1.89±0.76	0.59±0.12	0.64±0.10	0.73±0.15	74.88	1.11 ²	0.00*
T _i /T _{tot} %	40	15	15	16	-	-	-
T _e (sec)	1.76±0.83	3.58±0.79	4.24±1.08	4.42±0.82	103.18	3 ¹	0.00*
IM (a.u)	1.77±0.83	1.56±0.63	1.99±0.71	1.85±0.68	5.61	2.05 ²	0.00*
EM (a.u)	1.76±0.83	1.55±0.63	1.96±0.70	1.84±0.68	5.57	2.06 ²	0.00*
T _{tot} (sec)	4.71±1.74	4.20±0.89	5.23±1.14	5.02±0.90	11.77	1.66 ²	0.00*
RR (bpm)	14.11±3.85	14.93±2.89	12.11±2.68	13.34±2.33	8.68	1.92 ²	0.00*
%RC Ins	64.27±8.91	64.12±8.12	64.57±9.04	63.81±8.72	2.22	3 ¹	0.04*
%AB Ins	32.64±9.00	35.79±8.19	35.41±9.07	36.08±8.79	2.14	3 ¹	0.09
%RC Exp	67.57±8.77	64.60±8.06	64.82±9.23	62.74±9.14	3.30	3 ¹	0.02*
%AB Exp	32.33±8.86	35.31±8.18	35.16±9.26	37.17±9.22	3.31	3 ¹	0.02*

*Starred results significant at the 0.05 alpha level; ¹Sphericity assumed; ²Greenhouse-Geisser correction; TI (sec) = Inspiration time (seconds); T_i/T_{tot}% = percentage of time spent on inspiration; TE (sec) = expiration time (sec); IM (a.u) = inspiration magnitude (arbitrary units); EM (a.u) = Expiration magnitude (arbitrary units); T_{tot} (sec) = breathing cycle time (sec); RR (bpm) = respiratory rate (breaths per minute); %RC Insp = Ribcage percentage contribution to inspiration; %AB Insp = Abdominal percentage contribution to inspiration; %RC Exp = Ribcage percentage contribution to expiration; %AB Exp = Abdominal percentage contribution to expiration; DF = Degrees of Freedom

7.1.5 Post hoc analysis: pair-wise comparisons

Although the one way repeated measures ANOVA identified differences amongst the tasks, one of the limitations of the test is that it does not identify which tasks were different from which others. Any results that were found to be statistically significant were therefore followed up by post hoc tests to identify where the differences were for each breathing parameter. A decision was made to apply the Bonferroni adjustment for multiple comparisons in an attempt to account for the increased probability of any type one errors occurring due to multiple tests being carried out. Bonferroni adjustment for multiple comparisons multiplies the p value of the Least Significant Difference (LSD) (which is equivalent to performing multiple t tests) (Meier 2006), by the number of tests being performed and produces a new 'adjusted' p value. While this procedure has been criticised for being too conservative (Bender & Lange 1999), in this research, six paired comparisons were performed for each breathing parameter. This would increase the expected type one error rate from 20 to 30%, which was considered to be unacceptable. Post hoc comparisons were therefore performed for each parameter that was identified as being statistically significant from the one way repeated measures ANOVA. These results are presented in table 4.

Table 4: Post hoc analysis- Comparisons of speech breathing parameters between the speech tasks for 29 healthy young adults (n=29)

	Paired comparison	Mean difference	Standard error of the mean difference	p Value	95% Confidence interval of the mean difference	
					Lower	Upper
T_i(sec)	Reading and conversational speech	0.53	0.32	0.11	0.01;0.11	
	Reading and describing	0.14	0.37	0.00*	0.06;0.22	
	Describing and conversational speech	0.09	0.27	0.00*	0.03;0.14	
	Quiet breathing and reading	1.30	0.13	0.00*	1.03;1.57	
	Quiet breathing and describing	1.16	0.14	0.00*	0.85;1.46	
	Quiet breathing and conversational speech	1.25	0.14	0.00*	0.96;1.53	
T_E(sec)	Reading and conversational speech	0.94	0.16	0.00*	0.61;1.28	
	Reading and describing	0.66	0.16	0.00*	0.31;1.00	
	Describing and conversational speech	0.28	0.12	0.03*	0.02;0.54	
	Quiet breathing and reading	1.82	0.16	0.00*	1.47;2.16	
	Quiet breathing and describing	2.48	0.20	0.00*	2.07;3.17	
	Quiet breathing and conversational speech	2.76	0.20	0.00*	2.35;3.17	
IM (a.u)	Reading and conversational speech	0.42	0.10	0.00*	0.21;0.64	
	Reading and describing	0.28	0.08	0.00*	0.10;0.47	
	Describing and conversational speech	0.14	0.07	0.05	-0.00;0.28	
	Quiet breathing and reading	0.20	0.10	0.04*	0.00;0.41	
	Quiet breathing and describing	0.07	0.12	0.54	-0.18;0.34	
	Quiet breathing and conversational speech	0.22	0.13	0.11	-0.05;0.05	

EM (a.u)	Reading and conversational speech	0.41	0.10	0.00*	0.20;0.62
	Reading and describing	0.29	0.08	0.00*	0.11;0.47
	Describing and conversational speech	0.12	0.06	0.08	-0.25;0.01
	Quiet breathing and reading	0.21	0.10	0.04*	0.00;0.41
	Quiet breathing and describing	0.08	0.12	0.51	-0.17;0.33
	Quiet breathing and conversational speech	0.20	0.13	0.14	-0.70;0.47
Ttot (sec)	Reading and conversational speech	1.02	0.17	0.00*	0.66;1.38
	Reading and describing	0.81	0.19	0.00*	0.42;1.21
	Describing and conversational speech	0.20	0.13	0.13	0.06;0.48
	Quiet breathing and reading	0.50	0.30	0.10	-0.10;1.12
	Quiet breathing and describing	0.30	0.34	0.37	-0.39;1.00
	Quiet breathing and conversational speech	0.51	0.33	0.14	-0.18;1.20
RR (bpm)	Reading and conversational speech	2.82	0.49	0.00*	1.81;3.83
	Reading and describing	2.48	0.56	0.00*	1.32;3.36
	Describing and conversational speech	0.34	0.28	0.24	0.24;0.93
	Quiet breathing and reading	0.82	0.77	0.29	-0.75;2.40
	Quiet breathing and describing	1.65	0.79	0.04*	0.03;3.27
	Quiet breathing and conversational speech	1.99	0.79	0.01*	0.37;3.62

*Starred results significant at the 0.05 alpha level.

Bonferroni adjustment for multiple comparisons

T_I (sec) = Inspiration time (seconds); T_E (sec) = expiration time (sec); IM (a.u) = inspiration magnitude (arbitrary units); EM (a.u) = Expiration magnitude (arbitrary units); Ttot (sec) = breathing cycle time (sec); RR (bpm) = respiratory rate (breaths per minute).

Table 5 Post hoc comparisons for the regional contributions of the ribcage and abdomen to inspiration and expiration between each task in healthy young adults n=29

	Paired comparison	Mean difference	Standard error of the mean difference	p Value	95% Confidence interval of the mean difference	
					Lower	Upper
%RC Insp	Reading and spontaneous speech	0.44	1.74	0.80	-3.12	4.01
	Reading and describing	0.31	1.18	0.79	-2.11	2.79
	Describing and spontaneous speech	0.75	1.39	0.59	-2.09	3.60
	Quiet breathing and reading	3.14	1.55	0.05	-0.03	6.32
	Quiet breathing and describing	3.45	1.50	0.02*	0.37	6.53
	Quiet breathing and spontaneous speech	2.70	1.56	0.09	0.37	6.53
%RC Exp	Reading and spontaneous speech	0.21	1.73	0.90	-3.33	3.76
	Reading and describing	1.86	1.20	0.13	-0.60	4.33
	Describing and spontaneous speech	0.21	1.44	0.16	-0.87	5.03
	Quiet breathing and reading	2.96	1.60	0.07	-0.31	6.25
	Quiet breathing and describing	4.82	1.57	0.00*	1.61	8.04
	Quiet breathing and spontaneous speech	2.75	1.67	0.11	-0.68	6.18
%AB Exp	Reading and spontaneous speech	0.15	1.71	0.92	-3.36	3.67
	Reading and describing	1.85	1.20	0.13	-0.61	4.32
	Describing and spontaneous speech	2.00	1.44	0.17	-0.94	4.96
	Quiet breathing and reading	2.98	1.61	0.07	-0.32	6.28
	Quiet breathing and describing	4.83	1.58	0.00*	1.59	8.07
	Quiet breathing and spontaneous speech	2.82	1.68	0.10	-0.61	6.27

*Starred results significant at the 0.05 alpha level

Bonferroni corrections for multiple comparisons

%RCInsp = Ribcage percentage contribution to inspiration; %RCExp = Ribcage percentage contribution to expiration; %ABExp = Abdominal percentage contribution to expiration

Results from the post hoc analysis

The results from the post hoc analysis revealed that expiration time was significantly different between every pair-wise comparison, including between the two spontaneous speech tasks (describing and conversation). The remaining parameters were significantly different between some, but not all pair-wise comparisons. Statistically significant differences were most commonly identified between the linguistically constrained tasks (reading) and the linguistically unconstrained tasks (conversation and describing). These pair wise comparisons were found to be statistically significant for inspiration magnitude, expiration time and magnitude, breathing cycle time and respiratory rate. In contrast, apart from inspiratory and expiratory time, there were no statistically significant differences between the two spontaneous speech tasks (conversation and describing). Finally, there was no evidence to suggest that the regional contributions of the ribcage and abdomen were task specific within the speech tasks, although the results demonstrated that the regional contributions were different between quiet breathing and the describing task. These differences were significant for %RCInsp ($p=0.02$), %RCExp ($p=0.00$) and %ABExp ($p=0.00$).

7.1.6 Breathing and speech breathing variability

Breathing and speech breathing parameters were examined for their variability during each task (quiet breathing, reading, describing and conversational speech). The co-efficient of variation expressed as a percentage (CoV %) was used to assess the extent of the variability during the four minute recording period. This is the ratio of the standard deviation to the mean and calculated by $(SD/Mean) \times 100$. The higher the figure, the more variability was estimated to be present in the measure. The results in table 6 present the mean CoV (%) calculated from each four minute recording according to each breathing/speech breathing parameter.

	Quiet breathing (n=29)	Reading (n=29)	Describing (n=29)	Conversation (n=29)
TI CoV%	27.28±12.63	36.20±9.91	39.00±14.40	33.68±6.46
TE CoV%	23.86±10.36	46.70±9.61	43.71±9.60	48.99±10.73
IM CoV%	24.74±12.37	39.33±10.72	43.84±14.51	43.24±11.66
EM CoV%	25.05±12.43	44.56±9.14	46.93±11.92	50.30±13.71
Ttot Cov%	16.61±9.14	40.99±9.12	38.36±8.80	43.07±9.31
RR CoV%	27.28±3.85	19.35±2.89	19.35±2.41	22.13±2.68
%RCInsp CoV%	7.94±4.70	9.62±6.12	9.04±4.94	11.59±6.12
%ABInsp CoV%	16.66±10.08	16.97±14.86	15.32±5.37	23.54±19.05
%RCExp CoV%	8.97±6.17	13.11±6.75	16.83±11.66	17.23±11.57
%ABExp CoV%	17.84±9.26	22.40±7.26	26.97±15.68	26.16±13.17

CoV% = percentage Coefficient of Variation;

TI (sec) = Inspiration time (seconds); **TE (sec)** = expiration time (seconds); **IM (a.u)** = inspiration magnitude (arbitrary units); **EM (a.u)** = Expiration magnitude (arbitrary units); **Ttot (sec)** = breathing cycle time (seconds); **RR (bpm)** = respiratory rate (breaths per minute) **RC% Cont Insp** = Ribcage percentage contribution to inspiration; **AB%Cont Insp** = Abdominal percentage contribution to inspiration; **RC% Cont Exp** = Ribcage percentage contribution to expiration; **AB% Cont Exp** = Abdominal percentage contribution to expiration

Table 6 Mean Coefficient of Variation (%) according to each breathing parameter and task in healthy young adults (n=29)

The speech tasks were associated with the greatest variability (CoV%) for each parameter when compared with the quiet breathing task, apart from respiratory rate which had a greater variability when compared to the speech tasks. When exploring within the speech tasks, the inspiratory and expiratory magnitudes had the greatest variability during the linguistically unconstrained speech tasks (conversation and describing), while the reading task had the least. In comparison to the respiratory magnitudes and timing parameters, the smallest CoV% was observed for the regional contributions of the abdomen and ribcage respectively, where the spontaneous speech task (conversation) was associated with the greatest, and the quiet breathing task with the least variability.

7.1.7 Minute by minute analysis

A minute-by-minute analysis was performed for each breathing parameter and task, where the stability of the data was explored per one minute interval during the four minute recordings. There has been no previous study indicating whether speech breathing parameters remain stable over time. If speech breathing parameters were shown to remain stable across four minutes with little fluctuation, future studies could use shorter speech tasks and yet still produce meaningful data. This could reduce protocols, saving participant and research time, which would be particularly useful when examining speech breathing parameters in patient groups.

Table 7 presents the descriptive analysis for each breathing parameter according to each task for a period of one, two, three and four minutes respectively. One way repeated measures ANOVA was performed for each task and breathing parameter to determine whether any differences between minutes were statistically significant. Based on the findings presented in table 7, no statistically significant differences were found between any of the minutes for any of the breathing parameters or tasks suggesting that speech breathing patterns may remain stable throughout the recordings.

	Quiet Breathing task				Reading task				Describing task				Conversation task			
	Minutes				Minutes				Minutes				Minutes			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
T_i																
Mean	1.81	1.85	1.87	1.91	0.54	0.65	0.68	0.60	0.70	0.74	0.78	0.75	0.65	0.65	0.73	0.69
SD	(0.73)	(0.82)	(0.71)	(0.93)	(0.11)	(0.16)	(0.12)	(0.13)	(0.18)	(0.13)	(0.13)	(0.13)	(0.11)	(0.12)	(0.20)	(0.15)
T_e																
Mean	2.93	2.83	2.84	2.93	3.33	3.44	3.59	3.47	4.03	3.95	4.12	3.97	4.58	4.12	4.20	4.40
SD	(1.05)	(1.05)	(1.04)	(1.01)	(0.72)	(0.72)	(0.91)	(0.81)	(0.80)	(0.70)	(1.24)	(0.94)	(1.32)	(1.23)	(1.11)	(1.32)
IM																
Mean	0.90	0.89	0.95	0.98	0.79	0.98	0.81	0.82	0.92	0.90	0.99	0.95	1.07	1.01	1.08	1.09
SD	(0.41)	(0.40)	(0.49)	(0.54)	(0.31)	(0.39)	(0.30)	(0.31)	(0.39)	(0.31)	(0.49)	(0.45)	(0.42)	(0.32)	(0.44)	(0.47)
EM																
Mean	0.92	0.92	0.95	0.98	0.83	0.86	0.84	0.76	0.95	0.98	0.99	0.93	1.05	1.08	1.10	1.10
SD	(0.47)	(0.41)	(0.49)	(0.57)	(0.39)	(0.42)	(0.38)	(0.37)	(0.43)	(0.39)	(0.42)	(0.48)	(0.40)	(0.42)	(0.44)	(0.44)
T_{tot}																
Mean	4.72	4.70	4.78	4.89	3.98	4.01	4.15	4.01	4.79	4.65	4.79	4.62	5.13	4.88	5.08	4.87
SD	(1.71)	(1.86)	(1.69)	(1.90)	(0.5)	(0.88)	(1.00)	(0.91)	(0.92)	(0.89)	(1.29)	(0.92)	(1.19)	(1.20)	(1.21)	(1.21)
RR																
Mean	13.89	14.20	13.99	13.78	15.79	15.37	15.25	15.55	13.40	13.29	13.32	13.41	12.71	13.01	12.78	12.79
SD	(3.92)	(4.12)	(3.92)	(4.15)	(3.03)	(3.62)	(3.76)	(3.42)	(2.99)	(2.19)	(2.56)	(2.62)	(3.42)	(2.81)	(3.67)	(3.55)

T_i: Inspiration time; T_e: Expiration time; T_{tot}: Respiratory cycle time; RR: respiratory rate; IM: Inspiration Magnitude; EM: Expiration Magnitude; SD: Standard Deviation.

Table 7: Summary statistics: Minute by minute analysis for the healthy young adult group (n=29) during quiet breathing, reading, describing and conversational speech, at one, two, three and four minutes.

7.1.8 Stability of speech breathing parameters across different recording periods

While the minute-by-minute analysis suggested that breathing parameters remained stable from minute to minute, it was considered important to examine the data further to see if speech breathing parameters continued to remain stable when analysed during shorter or longer recordings.

Speech breathing parameters were therefore also analysed according to different time intervals, that is, 0-2 minutes, 0-3 minutes and 0-4 minutes. Table 8 presents the descriptive statistics for each task according to breathing parameter during these time periods. One way repeated measures ANOVA was used to test whether the differences between the time intervals (for each task and breathing parameter) were statistically significant.

The results in table 8 demonstrate that there was no statistically significant mean differences in any breathing parameters analysed during the different time intervals. These findings suggest that breathing parameters remained stable during both shorter (2 minutes) and longer time periods (4 minutes).

	Quiet breathing task			Reading task			Describing task			Conversation task		
	Recording length (minutes)			Recording length (minutes)			Recording length (minutes)			Recording length (minutes)		
	0-2	0-3	0-4	0-2	0-3	0-4	0-2	0-3	0-4	0-2	0-3	0-4
T_i												
Mean	1.87	1.86	1.88	0.58	0.59	0.59	0.71	0.71	0.71	0.63	0.66	0.66
SD	(0.79)	(0.74)	(0.75)	(0.14)	(0.13)	(0.13)	(0.14)	(0.13)	(0.13)	(.11)	(.13)	(.13)
T_e												
Mean	2.87	2.87	2.86	3.47	3.51	3.49	3.99	4.03	4.00	4.30	4.29	4.29
SD	(1.04)	(1.01)	(0.98)	(0.71)	(0.74)	(0.73)	(0.76)	(0.88)	(0.83)	(1.11)	(1.07)	(1.05)
IM												
Mean	0.91	0.92	0.93	0.83	0.84	0.85	0.95	0.96	0.95	1.05	1.05	1.07
SD	(0.42)	(0.43)	(0.45)	(0.35)	(0.35)	(0.35)	(0.39)	(0.39)	(0.38)	(0.38)	(0.38)	(0.39)
EM												
Mean	0.92	0.92	0.93	0.83	0.85	0.84	0.97	0.97	0.95	1.04	1.05	1.06
SD	(0.44)	(0.44)	(0.45)	(0.34)	(0.35)	(0.34)	(0.40)	(0.39)	(0.38)	(0.38)	(0.38)	(0.38)
T_{tot}												
Mean	4.73	4.73	4.74	4.05	4.10	4.08	4.70	4.73	4.72	4.93	4.95	4.95
SD	(1.77)	(1.72)	(1.69)	(0.82)	(0.83)	(0.83)	(0.82)	(0.92)	(0.87)	(1.15)	(1.11)	(1.09)
RR												
Mean	13.99	13.96	13.90	15.32	15.14	15.23	13.12	13.09	13.09	12.72	12.69	12.69
SD	(3.93)	(3.84)	(3.83)	(2.76)	(2.83)	(2.88)	(2.26)	(2.36)	(2.24)	(2.84)	(2.87)	(2.88)

T_i; Inspiration time, T_e Expiration time, T_{tot}; Respiratory cycle time, RR; Respiratory rate, IM; Inspiration magnitude, EM; Expiration magnitude

Table 8: Summary statistics: Comparison of breathing/speech breathing parameters for the healthy young adult group (n=29) among the different recording periods (0-2 minutes, 0-3 minutes, and 0-4 minutes) for each breathing/speech task

7.1.9 Summary of section one

Respiratory magnitudes and timing parameters were consistently significantly different between the ‘linguistically unconstrained’ (spontaneous speech/describing task) and the ‘linguistically constrained’ task (reading). These findings were less consistent when examining between the ‘unconstrained tasks’. Expiration time was identified as being the most responsive to the type of speech spoken, as statistically significant differences were found for every pair-wise comparison that was conducted, including between the linguistically unconstrained tasks. The regional contributions of the ribcage and abdomen were not speech ‘task specific’, although they were different between speech (describing) and quiet breathing. All breathing parameters remained stable when examined over the four minute recording period. The following table presents a summary of findings with respect to the hypotheses described in section 7.1.1.

Table 9 Summary of 7.1

Hypotheses	Summary of findings	Rejected/partially supported/supported?
HP1a	<ul style="list-style-type: none"> • The difference between spontaneous speech and reading was statistically significant for every parameter, apart from inspiration time. • The difference between the two spontaneous speech tasks (describing and conversation) was only found to be statistically significant for inspiration and expiration time. • The difference between each speech task and quiet breathing was only statistically significant for inspiration and expiration time. 	Partially supported
HP1b	<ul style="list-style-type: none"> • The difference between spontaneous speech and reading was statistically significant. • The difference between the two spontaneous speech tasks was not found to be statistically significant. • The difference between quiet breathing and speech was only found to be statistically significant for the reading task. 	Partially supported
HP1c	<ul style="list-style-type: none"> • There were no statistically significant differences between the speech tasks for %RCInsp, %RCExp, %ABExp. • The difference between quiet breathing and speech was only found to be statistically significant for the describing task. 	Partially supported

7.2 Section Two

Breathing and speech breathing patterns in healthy older adults

In this section, breathing and speech breathing patterns have been explored in a sample of 20 healthy 'older' adults (mean age 66.90 ± 8.49 years). Due to the known association between increasing age and changes in respiratory mechanics (Turner et al. 1968; Hoit & Hixon 1987; Janssens et al. 1999; Pride 2005), the decision to collect breathing and speech breathing pattern data from a sample of healthy 'older' adults was justified on the basis that comparisons could then be made with chronic respiratory disease patients with COPD or bronchiectasis (in section five) who are generally older. While the association between age and changes in respiratory mechanics remains unrefuted (Verschakelen & Demedts 1995; Watsford et al. 2007), any relationship between age and speech breathing patterns was unclear (Hoit & Hixon 1987; Hoit et al. 1990). The majority of studies examining the influence of age have been limited to quiet breathing patterns (Verschakelen & Demedts 1995; Parreira et al. 2010). Only a limited number of studies have examined the influence of age on speech breathing patterns, where these studies extracted speech breathing parameters from audiotapes and by using visual and aural detection of breathing cycles, which is now perceived as technologically dated (Hoit & Hixon 1987; Hoit et al. 1990). Published reports documenting the observation that speech breathing patterns are 'task specific' (Winkworth et al. 1994; Winkworth et al. 1995) have yet to be specifically confirmed in an older or patient population. It was therefore considered important to characterise breathing and speech breathing patterns within a healthy older sample and to examine their ability to differentiate between the various breathing and speech tasks.

7.2.1 Changes to the research protocol for collecting breathing and speech breathing pattern data in older adults

The findings from the first study informed the design of the second and third studies, and two specific changes were made to the protocol that was used to recruit healthy older adults and patients with chronic respiratory disease.

Firstly, it was observed that participants (from study one) found the four minute speaking tasks challenging to complete in terms of the duration. It was speculated that speaking continuously for four minutes would become even more difficult, and uncomfortable for patients with chronic respiratory disease, as it is acknowledged that patients with chronic respiratory disease often experience symptoms of breathlessness during speech (Kennedy 2007; Binazzi et al. 2011). Since breathing and speech breathing parameters were found to remain stable throughout a four minute recording period in a sample of 29 healthy adults (section 7.1.8), a decision was made to reduce the length of the speech recordings to a two minute period. This decision was made on the basis that this would minimise participant burden, while improving the efficiency of the protocol.

A second decision was made to remove the describing task from the protocol, and replace it with a counting task. This decision has been justified in detail in section 8.1.1.

7.2.2 Aims, Research questions and Hypotheses

Aims:

1. To characterise the breathing and speech breathing patterns from a sample of 20 healthy older participants during two minute periods of quiet breathing, reading, conversation and counting.
2. To compare the breathing and speech breathing patterns among the different tasks to assess if speech breathing patterns were 'task specific' within a healthy older sample.

Research question:

1. Do healthy older adults produce 'task specific' breathing and speech breathing patterns during a quiet breathing, reading, counting and conversational speech task?

Hypotheses developed after data collection:

HP2a There is a statistically significant difference in respiratory timing parameters (inspiration and expiration time, breathing cycle time

and respiratory rate) between a quiet breathing, reading, counting and conversation task in healthy older adults.

HP2b There is a statistically significant difference in respiratory magnitudes (inspiration and expiration magnitude) between a quiet breathing, reading, counting and conversation task in healthy older adults.

HP2c There is a statistically significant difference in the regional contributions of the rib cage and abdomen (%RCInsp, %ABInsp, %RCExp, %ABExp) between a quiet breathing, reading, counting and conversation task in healthy older adults.

7.2.3 Healthy older participant demographics

Twenty participants were included in the data analysis (8 males), where the mean age was 66.90 ± 8.49 . None of these participants reported any previous or current chronic respiratory diseases.

7.2.4 Analysis of Variance

Breathing and speech breathing parameters were compared between each task in order to test whether they were 'task specific' within a healthy older sample. After testing for normal distribution using the Shapiro-Wilk test, the data from each breathing parameter and task were found to be normally distributed. A decision was subsequently made to perform a one way repeated measures ANOVA to test for any statistically significant differences amongst the tasks, as each task was completed by the same participants. The Greenhouse Geisser correction was used when the assumptions of Mauchly's Test of Sphericity were violated. Table 10 presents the results from the one way repeated measures ANOVA according to each breathing parameter.

Results of the one way repeated measures ANOVA

The results in table 10 demonstrate that statistically significant differences were observed amongst the breathing and speech tasks for five breathing parameters, namely; inspiration ($F = 88.73$, $df = 1.23$, $p = 0.00$) and expiration time ($F = 11.23$, $df = 2.03$, $p = 0.00$), inspiration ($F = 11.49$, $df = 3$, $p = 0.00$) and expiration magnitude ($F = 10.75$, $df = 3$, $p = 0.00$), and the regional

contribution of the rib cage to inspiration ($F = 3.53$, $df = 1.92$, $p=0.00$). Each of these significant results was subsequently followed up by post hoc tests using the Bonferroni adjustment for multiple comparisons in order to identify where the differences were (table 11). A rationale for selecting the Bonferroni adjustment as a post hoc test was provided in section 7.1.5.

7.2.5 Results from the post hoc analysis

None of the parameters were significantly different between every task comparison (table 11). Unlike the younger adults, there were no significant differences between the linguistically unconstrained and constrained task for any of the parameters, apart from inspiration and expiration time. Apart from inspiration and expiration time, none of the breathing parameters were consistently different between the quiet breathing and speech task. There was no evidence to suggest that the regional contributions of the abdomen differed between the different speech tasks, although percentage contributions of the abdomen were significantly different between quiet breathing and speech (reading and spontaneous speech).

	Quiet breathing (n = 20)	Reading (n = 20)	Conversation (n = 20)	Counting (n = 20)	One way repeated measures ANOVA		
					F	df	p
T _i (sec)	1.74±0.50	0.59±0.12	0.68±0.16	0.52±0.13	88.73	1.23 ²	0.00*
T _e (sec)	2.82±0.81	3.86±0.84	4.70±1.11	4.40±1.88	11.23	2.03 ²	0.00*
IM (a.u)	1.69±0.63	1.46±0.44	1.51±0.64	1.20±0.27	11.49	3 ¹	0.00*
EM (a.u)	1.68±0.61	1.44±0.42	1.50±0.63	1.22±0.25	10.75	3 ¹	0.00*
T _{tot} (sec)	4.58±1.28	4.44±0.93	5.54±1.29	4.96±2.06	2.52	3 ¹	0.08
RR (bpm)	14.04±3.54	14.03±3.00	11.70±2.64	13.62±5.01	2.31	2.08 ²	0.08
%RCInsp	84.40±3.31	82.93±3.56	82.99±4.35	82.42±6.12	1.64	1.78 ²	0.21
%ABInsp	12.95±3.29	15.38±3.84	14.97±4.41	15.72±6.54	3.53	1.92 ²	0.04*
%RCExp	83.94±3.53	83.56±3.56	83.38±3.84	84.85±7.47	0.02	1.01 ²	0.88
%AbExp	13.42±3.69	14.66±4.20	14.75±3.75	14.04±7.54	0.04	1.03 ²	0.85

*Starred results significant at the 0.05 alpha level; ¹Sphericity assumed; ²Greenhouse-Geisser; **TI (sec)** = Inspiration time (seconds); Ti/Ttot% = percentage of time spent on inspiration; **TE (sec)** = expiration time (sec); **IM (a.u)** = inspiration magnitude (arbitrary units); **EM (a.u)** = Expiration magnitude (arbitrary units); **Ttot (sec)** = breathing cycle time (sec); **RR (bpm)** = respiratory rate (breaths per minute); **%RCInsp** = Ribcage percentage contribution to inspiration; **%ABInsp** = Abdominal percentage contribution to inspiration; **%RCExp** = Ribcage percentage contribution to expiration; **%ABExp** = Abdominal percentage contribution to expiration; DF = Degrees of Freedom;

Table 10 Breathing and speech breathing parameters in 20 healthy older adults during the various tasks: Descriptive statistics and results from the one way repeated measures ANOVA

	Paired comparison	Mean difference	Standard error of the mean difference	p Value	95% Confidence interval of the mean difference Lower: Upper
T_i (sec)	Reading and conversational speech	0.08	0.02	0.00*	0.14; -0.03
	Reading and counting	0.07	0.03	0.28	-0.02;0.16
	Counting and conversational speech	0.15	0.04	0.00*	0.03;0.28
	Quiet breathing and reading	1.14	0.11	0.00*	0.80;1.49
	Quiet breathing and counting	1.21	0.11	0.00*	0.87;1.55
	Quiet breathing and conversational speech	1.05	0.11	0.00*	0.71;1.40
T_e (sec)	Reading and conversational speech	0.83	0.28	0.04*	0.01;1.66
	Reading and counting	0.54	0.36	0.90	-0.52;1.60
	counting and conversational speech	0.29	0.44	1.00	-1.00;1.59
	Quiet breathing and reading	1.03	0.20	0.00*	0.43;1.64
	Quiet breathing and counting	1.58	0.44	0.01*	0.28;2.87
	Quiet breathing and conversational speech	1.87	0.29	0.00*	1.01;2.74
IM (a.u)	Reading and conversational speech	0.09	0.04	0.31	-0.03;0.21
	Reading and counting	0.17	0.05	0.01*	0.02;0.31
	counting and conversational speech	0.25	0.06	0.00*	0.06;0.45
	Quiet breathing and reading	0.01	0.03	1.00	-0.12;0.10
	Quiet breathing and counting	0.15	0.04	0.02*	0.02;0.29
	Quiet breathing and conversational speech	0.10	0.05	0.62	-0.07;0.27
Em (a.u)	Reading and conversational speech	0.08	0.04	0.33	-0.03;0.20
	Reading and counting	0.16	0.05	0.02*	0.02;0.31
	Counting and conversational speech	0.25	0.06	0.00*	0.05;0.44
	Quiet breathing and reading	0.00	0.03	1.00	-0.14;0.11
	Quiet breathing and Counting	0.15	0.04	0.02*	0.02;0.29
	Quiet breathing and conversational speech	0.09	0.05	0.73	-0.07;0.26
%AB insp	Reading and conversational speech	0.41	0.79	1.00	-2.74;1.92
	Reading and counting	0.33	0.91	1.00	-2.36;3.03
	Counting and conversational speech	0.74	1.18	1.00	-2.75;4.24
	Quiet breathing and reading	2.43	0.66	0.01*	0.48;4.38
	Quiet breathing and counting	2.76	1.22	0.21	-0.82;6.34
	Quiet breathing and conversational speech	2.02	0.66	0.04*	0.06;6.31

Table 11 Post hoc analysis in 20 healthy older adults: Pair-wise comparison between quiet breathing, reading, conversational speech and counting

7.2.5 Summary of section two

Only two breathing parameters (inspiration and expiration time) were significantly different between unconstrained speech tasks (spontaneous speech) and constrained speech tasks (reading). Apart from inspiration and expiration time, there was no evidence to suggest that any of the breathing parameters differed between each speech task in comparison to quiet breathing. Therefore, the evidence that speech breathing patterns are ‘task specific’ becomes less clear within an older population. The following table presents a summary of findings with respect to the hypotheses outlined in section 7.2.2

Table 12 Summary of 7.2

Hypothesis	Summary of findings	Rejected/partially supported/supported?
HP2a	<ul style="list-style-type: none"> Only two respiratory timing parameters (inspiratory and expiratory time) were able to differentiate between the tasks The differences between the quiet breathing and each speech task was statistically significant for inspiration and expiration time 	Partially supported
HP2b	<ul style="list-style-type: none"> The differences between reading and spontaneous speech were statistically significant. The differences between quiet breathing and the speech tasks was only found to be significant for the counting task 	Partially supported
HP2c	<ul style="list-style-type: none"> Significant differences were only identified for %ABInsp Significant differences were between quiet breathing and two speech tasks (reading and spontaneous speech) no significant differences were observed between the speech tasks. 	Partially supported

7.3 Section Three

Influence of age and sex on breathing and speech breathing parameters

In this section, the influence of two independent predictors (age and sex) on the total variance of each breathing and speech breathing parameter has been assessed using multiple linear regression in order to determine their overall contributions according to each parameter and breathing/speech task.

7.3.1 Aims, research questions and hypotheses

Aims:

1. To examine the influence of age on breathing and speech breathing parameters relating to timing, magnitudes and the regional contributions of the rib cage and abdomen in healthy adults during quiet breathing, reading and conversational speech.
2. To examine the influence of sex on breathing and speech breathing parameters relating to timing, magnitudes and the regional contributions of the rib cage and abdomen in healthy adults during quiet breathing, reading and conversational speech.

Research questions:

1. Are breathing and speech breathing parameters significantly influenced by age in healthy adults?
2. Are breathing and speech breathing parameters significantly influenced by sex in healthy adults?

Hypothesis developed after data collection:

- HP3a Respiratory timing parameters, magnitudes and regional contributions of the ribcage and abdomen obtained from healthy adults will be significantly influenced by age during quiet breathing, reading and conversation
- HP3b Respiratory timing parameters, magnitudes and regional contributions of the ribcage and abdomen obtained from healthy

adults will be significantly influenced by sex during quiet breathing, reading and conversation.

7.3.2 Multiple regression analysis results

Breathing and speech breathing pattern data from the healthy young adults and the healthy older adults were pooled and included in the model (n=49) to obtain data across a spectrum of different ages. The average age for the pooled data was 46.69 ± 19.28 years. Since the multiple linear regression analysis included data from study one and study two, the analysis could only be conducted for the quiet breathing task, reading, and conversation because the describing task was removed from the second and third studies due to the challenges faced by some participants when completing the task (see section 8.1.1). The results in tables 13-15 summarise the linear model of predictors (age and sex) on each breathing parameter during quiet breathing (table 13), reading (table 14) and spontaneous speech (table 15).

In each regression, the histograms and p-p plots were assessed for linearity, independence of errors, homoscedasticity and normality of error distribution. The regression standardised residual histograms looked approximately bell-shaped and showed normal distribution of residuals. The P-P plots also demonstrated reasonably distributed residuals. The assumption of homoscedasticity was met since the data points were randomly dispersed throughout the plot in support the validity of the model. Any exceptions to these assumptions have been presented separately.

Quiet breathing task

Table 13. Influence of age and sex on breathing parameters during the quiet breathing task in healthy adults (n=49) – results of the linear regression

	Mean±SD	R ²	Constant	AGE				SEX			
				B	SE	95% CI for B	p	B	SE	95% CI for B	p
T _I (sec)	1.83±0.67	0.03	2.28	-0.001	0.005	-0.11;0.009	0.84	-0.25	0.19	-0.65;0.14	0.19
T _E (sec)	2.19±0.97	0.12	1.55	0.01	0.007	0.004;0.03	0.01*	-0.11	0.27	-0.66;0.43	0.67
IM (a.u)	1.74±0.75	0.03	1.80	-0.007	0.006	-0.01;0.005	0.23	0.16	0.22	-0.28;0.60	0.46
EM (a.u)	1.73±0.74	0.04	1.79	-0.007	0.006	-0.01;0.004	0.21	0.16	0.21	-0.27;0.60	0.44
T _{tot} (sec)	4.66±1.56	0.07	5.49	0.002	0.01	-0.02;0.02	0.83	-0.59	0.45	-1.52;0.32	0.19
RR (bpm)	14.08±3.69	0.06	11.87	-0.01	0.02	-0.07;0.03	0.54	1.88	1.06	-0.26;4.02	0.08
%RC _{Insp}	74.26±11.09	0.37	55.56	0.3	0.06	0.21;0.48	0.00*	1.59	2.61	-3.67;6.86	0.54
%AB _{Insp}	24.60±12.13	0.42	45.67	-0.40	0.07	-0.54;-0.25	0.00*	-1.44	2.76	-7.00;4.10	0.60
%RC _{Exp}	74.25±10.76	0.37	56.16	0.33	0.06	0.20;0.46	0.00*	1.52	2.15	-3.59;6.64	0.55
%AB _{Exp}	24.61±11.81	0.41	44.95	-0.39	0.06	-0.53;-0.25	0.00*	-1.33	2.69	-6.75;4.09	0.62

B =Unstandardised Beta; SE = Standard Error; R²=Coefficient of determination; TI (sec) = Inspiration time (seconds); Ti/Ttot% = percentage of time spent on inspiration; TE (sec) = expiration time (seconds); IM (a.u) = inspiration magnitude (arbitrary units); EM (a.u) = Expiration magnitude (arbitrary units); T_{tot} (sec) = breathing cycle time (seconds); RR (bpm) = respiratory rate (breaths per minute); %RC Insp = Ribcage percentage contribution to inspiration; %AB Insp = Abdominal percentage contribution to inspiration; %RC Exp = Ribcage percentage contribution to expiration; %AB Exp = Abdominal percentage contribution to expiration.

Reading task

Table 14. Influence of age and sex on breathing parameters during the reading task in healthy adults (n=49) – Results of the multiple linear regression

	Mean±SD	R ²	Constant	AGE				SEX			
				B	SE	95% CI for B	p	B	SE	95% CI for B	p
T _I (sec)	0.59±0.12	0.01	0.53	0.001	0.001	-0.001;0.002	0.56	0.01	0.03	-0.05;0.09	0.63
T _E (sec)	3.69±0.81	0.03	3.14	0.006	0.006	-0.006;0.019	0.31	0.16	0.24	-0.32;0.64	0.50
IM (a.u)	1.52±0.56	0.10	1.28	-0.005	0.004	-0.01;0.003	0.19	0.31	0.15	-0.007;0.63	0.05
EM (a.u)	1.50±0.55	0.10	1.25	-0.006	0.004	-0.10;0.003	0.17	0.31	0.15	0.003;0.63	0.05
T _{tot} (sec)	4.30±0.19	0.02	3.73	0.006	0.007	-0.008;0.02	0.40	0.19	0.26	0.34;0.73	0.48
RR (bpm)	14.57±2.94	0.03	16.28	-0.20	0.02	-0.70;0.01	0.22	-0.28	0.86	-2.01;1.45	0.74
%RC Insp	71.80±11.43	0.43	51.96	0.38	0.06	0.25;0.51	0.00*	1.30	2.56	-3.86;6.47	0.61
%AB Insp	27.46±12.15	0.44	48.29	-0.42	0.06	-0.55;-0.28	0.00*	-0.77	2.69	-6.20;4.65	0.77
%RC Exp	72.34±11.47	0.44	52.69	0.39	0.06	0.25;0.52	0.00*	0.84	2.56	-4.31;6.00	0.74
%Ab Exp	26.88±12.27	0.45	47.75	-0.42	0.07	-0.56;-0.28	0.00*	-0.55	2.70	-6.00;4.88	0.83

B =Unstandardised Beta; SE = Standard Error; R²=Coefficient of determination; **TI (sec)** = Inspiration time (seconds); Ti/Ttot% = percentage of time spent on inspiration; **TE (sec)** = expiration time (seconds); **IM (a.u)** = inspiration magnitude (arbitrary units); **EM (a.u)** = Expiration magnitude (arbitrary units); **Ttot (sec)** = breathing cycle time (seconds); **RR (bpm)** = respiratory rate (breaths per minute); **%RC Insp** = Ribcage percentage contribution to inspiration; **%AB Insp** = Abdominal percentage contribution to inspiration; **%RC Exp** = Ribcage percentage contribution to expiration; **%AB Exp** = Abdominal percentage contribution to expiration

Conversational speech task

**Table 15 Influence of age and sex on breathing parameters during the conversational speech task in healthy adults (n=49)
Results of the multiple linear regression**

	Mean±SD	R ²	Constant	AGE				SEX			
				B	SE	95% CI for B	p	B	SE	95% CI for B	p
T _i (sec)	0.66±0.13	0.09	0.51	0.002	0.001	0.00;0.004	0.06	0.03	0.03	-0.40;0.11	0.34
T _e (sec)	4.60±1.10	0.06	3.55	0.01	0.008	-0.007;0.02	0.24	0.36	0.32	-0.27;1.01	0.25
IM (a.u)	1.96±0.68	0.002	2.00	-0.002	0.005	-0.01;0.009	0.76	0.02	0.20	-0.39;0.43	0.91
EM (a.u)	1.93±0.67	0.002	1.97	-0.002	0.005	-0.01;0.009	0.75	0.02	0.20	-0.38;0.42	0.90
T _{tot} (sec)	5.31±1.20	0.07	4.13	0.01	0.00	-0.005;0.03	0.16	0.28	0.34	-0.31;1.07	0.27
RR (bpm)	11.94±2.65	0.08	14.96	-0.30	0.02	-0.70;0.009	0.12	-0.82	0.75	-2.35;0.70	0.28
%RC Insp	72.09±11.78	0.42	54.17	0.39	0.06	0.25;0.53	0.00*	-0.42	2.67	-5.81;4.97	0.87
%AB Insp	27.07±12.60	0.44	46.24	-0.43	0.07	-0.58;-0.29	0.00*	0.84	2.79	-4.78;6.47	0.76
%RC Exp	72.39±11.85	0.41	54.71	0.39	0.07	0.25;0.53	0.00*	-0.53	2.71	-5.90;4.93	0.84
%Ab Exp	26.83±12.58	0.42	45.62	-0.43	0.07	-0.58;-0.29	0.00*	0.98	2.80	-4.66;6.64	0.72

B =Unstandardized Beta; SE = Standard Error; R²=Coefficient of determination; **TI (sec)** = Inspiration time (seconds); T_i/T_{tot}% = percentage of time spent on inspiration; **TE (sec)** = expiration time (seconds); **IM (a.u)** = inspiration magnitude (arbitrary units); **EM (a.u)** = Expiration magnitude (arbitrary units); **T_{tot} (sec)** = breathing cycle time (seconds); **RR (bpm)** = respiratory rate (breaths per minute); **%RC Insp** = Ribcage percentage contribution to inspiration; **%AB Insp** = Abdominal percentage contribution to inspiration; **%RC Exp** = Ribcage percentage contribution to expiration; **%AB Exp** = Abdominal percentage contribution to expiration

7.3.3 Assessing the variance of breathing and speech breathing parameters in healthy adults explained by two independent predictors (age and sex)

Respiratory timings and magnitudes

Multiple linear regression was used to assess the relationship between each outcome variable (breathing parameter) and two independent predictors (age and sex). Based on the summary findings in table 13, there was no evidence to suggest that age or sex had any significant influence on any of the respiratory timing parameters, or magnitude, apart from expiration time during the quiet breathing task. There was a minor indication that the variance of expiration time could partly be explained by age ($B = 0.01$, $p=0.01$), where the beta weights indicated that a unit increase of one year was associated with a predicted increase of 0.01 seconds. However, while the overall fit of the model was found to be statistically significant ($p=0.01$), the correlation was found to be extremely weak ($R^2 = 0.12$). This significant result was not observed during the other tasks (reading or conversational speech).

Regional contributions of the rib cage and abdomen

Age was found to significantly influence four breathing parameters (regional contributions of the ribcage and abdomen to inspiration and expiration) during every task ($p<0.05$). By looking at the R^2 values (the proportion of variance in the dependent variables that could be explained by the independent variables), the independent variables explained between 41% and 44% of the variability of the regional contributions of the rib cage and abdomen during inspiration and expiration. This variance was significant for age ($p<0.05$), but not sex. In general, the regression suggests that increasing age was associated with a greater ribcage and smaller abdominal contribution. For example, during the quiet breathing task, a unit increase of one year was associated with a 0.34% increase and 0.40% decrease in ribcage and abdominal contributions respectively. However, while these results were found to be statistically significant, the correlation was found to be weak (between 0.41 and 0.45). Furthermore, the regression standardised residual histograms for %RCInsp, %ABInsp, %RCExp and %ABExp appeared to be more negatively skewed, and the P-P plots demonstrated some deviations from normality suggesting that residuals were not normally distributed. However, the assumption of the

homoscedasticity was met as the data points were randomly spread around zero, with no obvious change in the variation of the residuals across the range of predicted values. Since the regression standardised residual histograms, P-P plots and scatter plots of the residuals were similar for each parameter representing the regional contributions of the ribcage and abdomen during every task, the histograms and plots (figures 17-19) have only been presented for one variable, namely %RCExp during the quiet breathing task in order to avoid repetition.

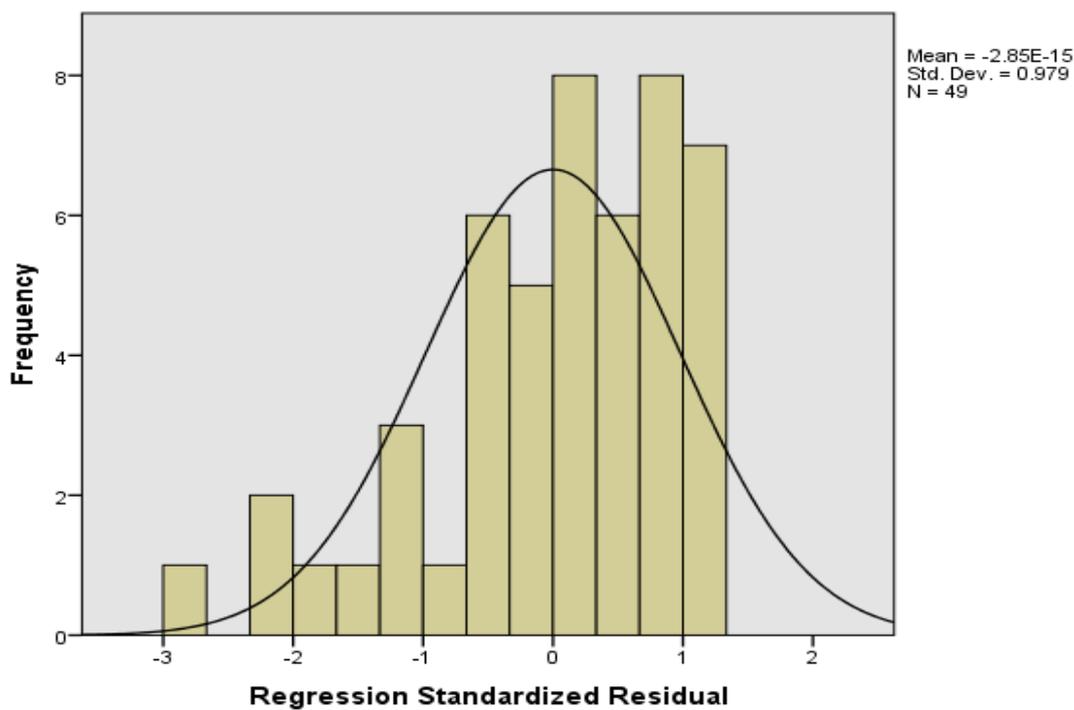


Figure 17 Regression standardised residual histogram of ribcage data (%RCExp) during the quiet breathing task demonstrates a negatively (right) skewed distribution

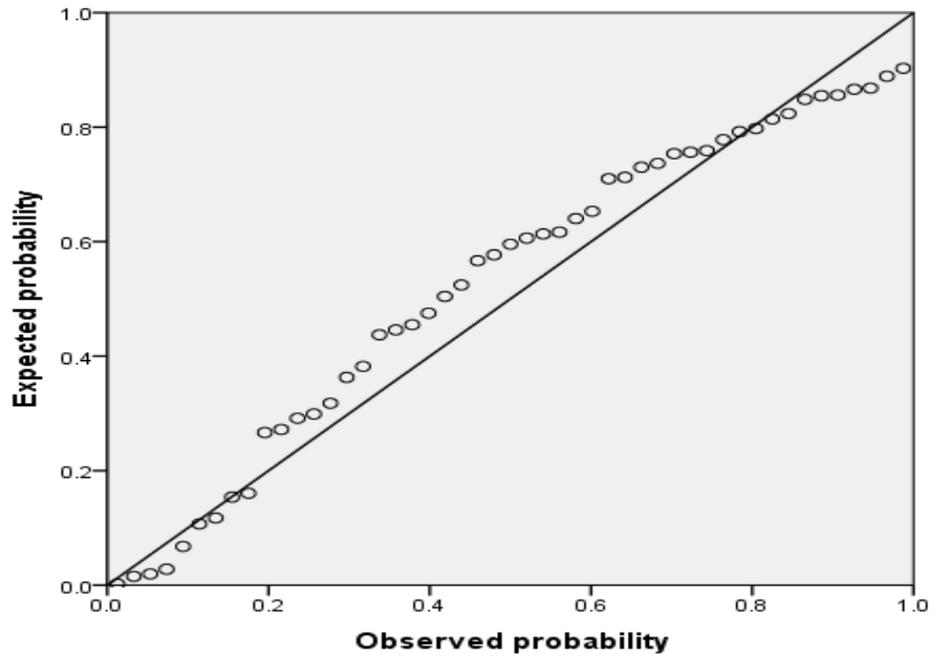


Figure 18 P-P plot for regression model for %RCEp during the quiet breathing task demonstrating some deviations from normality which suggests that residuals were not normally distributed

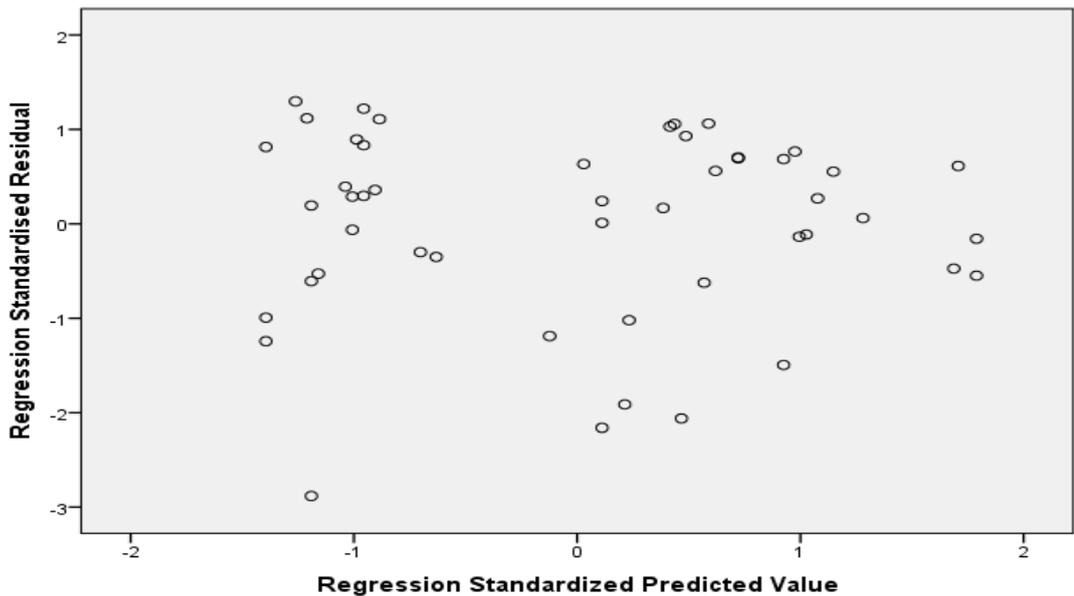


Figure 19 Scatter plot of the residuals of the regression model for %RCEp during the quiet breathing task demonstrating no obvious change in the variation of residual value across the range of predicted values

7.3.4 Summary of section three

No association between breathing parameters and sex could be detected within this sample. Age was found to have some influence on some parameters: the relative contribution of age to the total variance of each parameter was found to be significant for the regional contributions of the ribcage and abdomen. However, due to the weak correlations and sub-optimal p-p plots and standardised histograms, these findings need to be interpreted with caution and are by no means conclusive. The following table presents a summary of findings with respect to the hypotheses described in section 7.3.1.

Table 16 Summary of section 7.3

Hypotheses	Summary of findings	Rejected/partially supported/supported?
HP3a	<ul style="list-style-type: none"> Expiration time was significantly influenced by age during the quiet breathing task, although the correlation was found to be extremely weak ($R^2=0.12$) %RCInsp, %ABInsp, %RCExp, %ABExp were significantly influenced by sex during every task, although the actual correlation was also found to be weak. 	Partially supported
HP3b	<ul style="list-style-type: none"> Sex was not found to have any significant influence on any of the respiratory parameters. 	Rejected

7.4 Section Four

Breathing and speech breathing patterns characterised in adults with self-reported asthma, and patients with COPD and bronchiectasis

7.4.1 Introduction

In this section, breathing and speech breathing patterns have been characterised within groups with self-reported asthma, COPD and bronchiectasis. Each parameter was compared between the various breathing and speech tasks in order to examine task specificity within these groups. Patients with COPD and bronchiectasis were then pooled into one group (referred to as pooled patients with chronic respiratory disease (CRD)), on the basis of their similarities in age and available spirometry. Demographic and anthropometric data are firstly presented according to primary diagnosis and pooled patients with CRD.

7.4.2 Aims, Research questions and Hypotheses

Aims:

1. To characterise the breathing and speech breathing patterns obtained from a patients with one of 3 chronic respiratory diseases during various speech tasks.
2. To compare the breathing and speech breathing patterns among the different tasks, to assess if speech breathing patterns were task specific within each disease group.

Research questions:

1. Do adults with self-reported asthma produce 'task specific' breathing patterns?
2. Do patients with CRD (COPD and bronchiectasis) produce 'task specific' breathing patterns

Hypotheses developed after data collection:

- HP4a** There is a statistically significant difference in respiratory timing parameters, magnitudes and regional contributions of the ribcage and abdomen between quiet breathing, reading, describing and a spontaneous speech task in **participants with self-reported asthma.**
- HP4b** There is a statistically significant difference in respiratory timing parameters, magnitudes and regional contributions of the ribcage and abdomen between quiet breathing, reading, counting and a spontaneous speech task in **patients with bronchiectasis.**
- HP4c** There is a statistically significant difference in respiratory timing parameters, magnitudes and regional contributions of the ribcage and abdomen between quiet breathing, reading, counting and a spontaneous speech task in **patients with COPD.**
- HP4d** There is a statistically significant difference in respiratory timing parameters, magnitudes and regional contributions of the ribcage and abdomen between quiet breathing, reading, counting and a spontaneous speech task in **pooled patients with CRD.**

7.4.3 Demographic and anthropometric data (self-reported asthma, bronchiectasis and COPD, and pooled patients CRD)

Adults with self-reported asthma were recruited during the first study. Patients with a diagnosis of COPD or bronchiectasis were recruited during the third study. The demographic and anthropometric data are firstly presented according to primary diagnosis (self-reported asthma, COPD and bronchiectasis) (table 17). Baseline data from the COPD and bronchiectasis patients who took part in study three were then pooled to create an older chronic respiratory disease group for further analysis. The self-reported asthma data were not included in this pooled group on the grounds that a) the asthma diagnosis was unconfirmed by a clinician and b) they were younger in age and c) no spirometry was available for them. In the patient groups lung function (spirometry) data could only be presented for 11 patients (COPD = 7,

bronchiectasis = 4), as these data were missing from patient medical notes in the other 9 patients.

	By primary diagnosis			pooled patients with CRD (n=20)
	COPD (n=14)	Bronchiectasis (n=6)	Self-reported asthma (n=11)	
Age (years) Mean±sd	69.36±9.64	70.50±7.23	28.55±6.15	69.70±8.81
Sex	M = 7, F = 7	M = 1, F = 5	M= 1, F = 10	M = 8, F = 12
Length of illness (years) Mean Range	6.81 (1-14)	4.40 (1-10)	-	6.14 (1-14)
FEV₁ (% of predicted) Mean (SD) n = 7	46.43 (14.82) n = 7	51.57 (10.17) n = 4	-	48.36 (13.04) n = 11
FVC (% of predicted) Mean (SD) n = 7	72.00 (21.97) n = 7	81.50 (10.47) n = 4	-	75.45 (18.59) n = 11
FEV₁/FVC Mean (SD) n = 7	0.53 (0.16) n = 7	0.48 (0.11) n = 4	-	0.51 (0.14) n = 11

FEV₁: Forced Expiratory Volume in one second; FVC: Forced Vital Capacity.

Table 17 Demographic and anthropometric data from participants with chronic respiratory disease according to individual pathology, and the pooled patients with COPD and bronchiectasis

Demographic and lung function data were compared between the COPD and bronchiectasis groups to determine whether there were any statistically significant differences between them. Both data sets were examined for normal distribution using the Shapiro-Wilk test, and the data was found to be normally distributed for each variable. Independent sample t tests were used to test for whether there were any statistically significant differences between the COPD and bronchiectasis group (table 18).

	COPD	BR	Mean Diff.	t	df	p Value
Age (years) Mean range	69.36 (51-84)	70.50 (61-83)	1.14	0.25	18	0.79
Length of illness (years) Mean Range	6.81 (1-14)	4.40 (1-10)	2.48	0.86	18	0.39
FEV₁ (% of predicted) Mean SD	46.43 (14.82)	51.57 (10.17)	5.32	0.63	9	0.54
FVC (% of predicted) Mean SD	72.00 (21.97)	81.50 (10.47)	9.50	0.80	9	0.44
FEV₁/FVC Mean SD	0.53 (0.16)	0.48 (0.11)	0.04	0.49	9	0.63

FEV₁ = Forced Expiratory Volume in one second; FVC = Forced Vital Capacity; BR = Bronchiectasis

Table 18 Demographic and lung function data; comparison between COPD and bronchiectasis – results from the independent t tests

Of the 20 patients with a diagnosis of chronic respiratory disease, 14 had COPD (7 males) and 6 had bronchiectasis (1 male). On average, participants with COPD had their illness for longer (6.81 years) than those with bronchiectasis (4.40 years). When looking at the lung function data, all these patients were considered to have ‘severe’ airflow obstruction based on the GOLD classification of airways obstruction guidelines (FEV_{1pp} <50%) (GOLD 2014). Airflow obstruction was slightly worse for patients with COPD. However, the results of the independent t tests demonstrated no statistically significant differences for any demographic or lung function data between those with COPD and bronchiectasis in this sample. This supported the decision to pool the data from these two diagnostic groups for further analysis (see section 7.4.7).

The 11 participants with self-reported asthma (10 females) had a mean age of 28.55±6.15. While asthma status was not confirmed with formal lung function testing, 10 of the 11 participants reported using a combination of steroidal and non-steroidal (β - agonist) bronchodilators when required. Of these 10 participants, 1 used Fostair (β - agonist), 3 administered a combination of

Salbutamol and Ventolin (both β agonists), 1 used Ventolin and Becotide (steroid) and the remaining 5 used Ventolin.

7.4.4 Characterising breathing and speech breathing patterns in adults with a self-reported history of asthma

Descriptive statistics (mean and SD) were calculated for each breathing parameter during quiet breathing, reading, describing and conversational speech. The self-reported asthma group had been given the describing task during study one.

Task specificity was tested for each breathing and speech breathing parameter using a one way repeated measures ANOVA. All data were found to be normally distributed when assessed using the Shapiro Wilk test. The Greenhouse-Geisser correction was used when the assumptions of Mauchly's Test of Sphericity were violated. Any statistically significant results from the ANOVA were subsequently followed by post hoc tests using the Bonferroni adjustment for multiple comparisons. This analysis was performed for each group, but will only be described here, to avoid repetition.

Self-reported asthma (n=11)

Descriptive analysis

On visual inspection of the data (table 19), adults who reported a history of asthma appeared to produce breathing patterns similar to those previously observed for healthy young (section 7.1.4) and healthy older adults (section 7.2.4), during a quiet breathing, reading and conversational speech task. On average, the linguistically constrained task (reading) was associated with the shortest respiratory magnitudes and timing components (expiratory time and breathing cycle time), and had the fastest respiratory rate.

	Quiet breathing (n = 11)	Reading (n = 11)	Conversation (n = 11)	Describing (n = 11)	One way repeated measures ANOVA results		
					F	df	p
T _i (sec)	1.75±0.38	0.52±0.11	0.49±0.08	0.62±0.15	9.17	1.18 ²	0.00*
T _i /T _{tot} (%)	37	13	11	14	-	-	-
T _e (sec)	2.89±0.60	3.29±0.84	3.84±0.76	3.70±1.12	4.74	1.64 ²	0.02*
IM (a.u)	1.62±0.48	1.60±0.79	2.01±0.67	2.03±0.78	3.81	3 ¹	0.02*
EM (a.u)	1.62±0.47	1.58±0.79	2.00±0.67	1.99±0.76	3.52	3 ¹	0.02*
T _{tot} (sec)	4.67±0.93	3.84±0.90	4.39±0.79	4.36±1.22	2.34	1.47 ²	0.14
RR (bpm)	13.42±2.80	16.40±3.58	14.21±2.34	14.66±3.26	3.33	1.86 ²	0.06
%RC Insp	62.70±4.99	63.35±6.22	64.51±4.18	65.89±4.24	1.15	1.68 ²	0.33
%AB Insp	37.28±5.98	36.63±6.28	35.42±4.24	34.02±4.33	1.19	1.69 ²	0.32
%RC Exp	62.95±5.34	62.48±6.81	64.39±5.22	64.30±8.36	0.40	3 ¹	0.74
%AB Exp	37.03±5.34	37.50±6.85	35.55±5.24	35.59±8.44	0.43	3 ¹	0.72

*Starred results significant at the 0.05 alpha level; ¹Sphericity assumed; ²Greenhouse-Geisser; T_i (sec) = Inspiration time (seconds); T_e (sec) = expiration time (seconds); IM (a.u) = Inspiration magnitude (arbitrary units); EM (a.u) = Expiration magnitude (arbitrary units); T_{tot} (sec) = breathing cycle time (seconds); RR (bpm) = respiratory rate (breaths per minute); %RC Insp = Ribcage percentage contribution to inspiration; %AB Insp = Abdominal percentage contribution to inspiration; %RC Exp = Ribcage percentage contribution to expiration; %AB Exp = Abdominal percentage contribution to expiration; DF = Degrees of Freedom.

Table 19 Breathing and speech breathing parameters in 11 adults with a self-reported history of asthma during quiet breathing reading, describing and conversational speech: Descriptive statistics and results of the one way repeated measures ANOVA

	Paired-wise comparison	Mean difference	Standard error of the mean difference	p Value	95% Confidence interval of the mean difference Upper bound; lower bound
T_i (sec)	Reading and conversational speech	0.03	0.02	1.00	-0.05; 0.11
	Reading and describing	0.09	0.04	0.29	-0.23;0.04
	Describing and conversational speech	0.12	0.03	0.04*	0.01;0.24
	Quiet breathing and reading	1.22	0.11	0.00*	0.86;1.59
	Quiet breathing and describing	1.13	0.13	0.00*	0.68;1.57
	Quiet breathing and conversational speech	1.25	0.11	0.00*	0.87;1.64
T_e (sec)	Reading and conversational speech	0.54	0.19	0.12	-0.10;1.19
	Reading and describing	0.40	0.28	1.00	-0.52;1.33
	Describing and conversational speech	-0.13	0.16	1.00	-0.68;0.40
	Quiet breathing and reading	0.40	0.24	0.75	-0.39;1.20
	Quiet breathing and describing	0.18	0.39	0.40	-0.48;2.11
	Quiet breathing and conversational speech	0.95	0.31	0.08	-0.09;1.99
IM (a.u)	Reading and conversational speech	0.40	0.14	0.10	-0.06;0.87
	Reading and describing	0.42	0.17	0.22	-0.15;1.01
	Describing and conversational speech	0.02	0.12	1.00	-0.39;0.43
	Quiet breathing and reading	0.02	0.15	1.00	-0.47;0.52
	Quiet breathing and describing	0.40	0.22	0.64	-0.34;1.15
	Quiet breathing and conversational speech	0.38	0.17	0.30	-0.18;0.94
Em (a.u)	Reading and conversational speech	0.41	0.15	0.12	-0.08;0.90
	Reading and describing	0.40	0.17	0.27	-0.17;0.98
	Describing and conversational speech	0.01	0.13	1.00	-0.42;0.44
	Quiet breathing and reading	0.03	0.15	1.00	-0.45;0.53
	Quiet breathing and describing	0.36	0.22	0.77	-0.35;1.08
	Quiet breathing and conversational speech	0.37	0.17	0.32	-0.18;0.93

***Starred results significant at the 0.05 alpha level**

TI = Inspiratory time (seconds), **TE** = Expiratory time (seconds); **IM** = Inspiratory Magnitude (arbitrary units); **EM** = Expiratory magnitude (arbitrary units)

Table 20 Adults with a self-reported history of asthma (n=11): Results from the post hoc analysis – pairwise comparisons between quiet breathing, reading describing and conversational speech.

Task specificity in adults who reported a history of asthma

The findings from the one way repeated measures ANOVA revealed statistically significant differences among the tasks for four breathing parameters, namely; inspiration time ($F=9.17$, $df=1.18$, $p=0.00$), expiration time ($F=4.74$, $df=1.64$, $p=0.02$), inspiration magnitude ($F=3.18$, $df=3$, $p=0.02$) and expiration magnitude ($F=3.52$, $df=3$, $p=0.02$). However, the examination of the post hoc results revealed that the paired comparisons were only significant for inspiration time. Conflicts between a significant ANOVA and non-significant post hoc test are not an uncommon finding. Post hoc testing using Bonferroni corrections for multiple comparisons is considered as a conservative test, however its use in the current investigation was justified on the basis that multiple comparisons were being performed, which could increase type one error rate. Pair-wise comparisons for inspiration time suggested that the majority of differences were observed between quiet breathing and each of the speech tasks: reading ($p=0.00$), describing ($p=0.00$) and conversational speech ($p=0.00$). When examining between the speech tasks, statistically significant differences were only identified between describing and conversational speech ($p=0.04$).

7.4.5 Characterising breathing and speech breathing patterns in patients with bronchiectasis

Breathing and speech breathing patterns will now be examined for their ability to differentiate between the various breathing and speech tasks (quiet breathing, reading, conversational speech and counting), in six patients with a clinical diagnosis of bronchiectasis (table 21). Due to some missing data sets (which arose from technical failures during the data collection phase - see section 7.6.8), data from two participants had to be removed from the quiet breathing task. ANOVA requires full data sets when comparing between the tasks, therefore the results from the comparative analysis could only be based on four participants. Descriptive statistics and results from the one way repeated measures ANOVA are firstly presented, followed by the results from the post hoc analysis (table 22).

	Quiet breathing (n =4)	Reading (n = 6)	Conversation (n =6)	Counting (n =6)	One way repeated measures ANOVA results		
					F	df	p
T _i (sec)	1.43±0.13	0.63±0.09	0.66±0.12	0.58±0.21	43.39	3 ¹	0.00*
T _e (sec)	2.19±0.17	3.57±0.72	3.56±0.76	3.30±1.51	4.68	3 ¹	0.03*
IM (a.u)	1.19±0.42	1.20±0.48	1.31±0.87	0.97±0.10	1.13	3 ¹	0.38
EM (a.u)	1.20±0.45	1.19±0.48	1.28±0.59	0.98±0.12	1.13	3 ¹	0.38
T _{tot} (sec)	3.64±0.84	4.26±0.74	4.26±0.79	3.92±1.66	0.88	1.21 ²	0.43
RR (bpm)	17.25±4.01	14.55±2.2.7	14.62±2.99	17.60±6.74	1.00	3 ¹	0.43
%RC Ins	65.33±11.43	60.78±13.82	54.04±16.24	53.11±18.01	4.05	3 ¹	0.04*
%AB Ins	33.92±11.74	38.94±13.87	45.70±16.18	46.41±18.00	4.10	3 ¹	0.04*
%RC Exp	58.71±12.71	58.90±13.77	53.02±16.61	58.32±12.98	2.77	3 ¹	0.10
%AB Exp	34.35±12.19	40.93±13.79	46.45±16.81	41.27±13.00	2.68	3 ¹	0.11

*Starred results significant at the 0.05 alpha level; ¹Sphericity assumed; ²Greenhouse-Geisser;

TI (sec) = Inspiration time (seconds); TE (sec) = expiration time (sec); IM (a.u) = inspiration magnitude (arbitrary units); EM (a.u) = Expiration magnitude (arbitrary units); T_{tot} (sec) = breathing cycle time (sec); RR (bpm) = respiratory rate (breaths per minute); %RC Insp = Ribcage percentage contribution to inspiration; %AB Insp = Abdominal percentage contribution to inspiration; %RC Exp = Ribcage percentage contribution to expiration; %AB Exp = Abdominal percentage contribution to expiration; DF = Degrees of Freedom

Table 21 Breathing and speech breathing parameters in **6 patients with bronchiectasis** during quiet breathing reading, counting and conversational speech: Descriptive statistics and results from the one way repeated measures ANOVA (n=4)

	Paired comparison	Mean difference	Standard error of the mean difference	p Value	95% Confidence interval of the mean difference upper bound; lower bound
T_i (sec)	Reading and spontaneous speech	0.00	0.07	1.00	-1.39;-0.24
	Reading and counting	0.04	0.08	0.02*	-1.42;-0.22
	Counting and spontaneous speech	0.04	0.11	1.00	-0.65;0.75
	Quiet breathing and reading	0.82	0.09	0.02*	0.22;1.42
	Quiet breathing and counting	0.86	0.06	0.00*	0.43;1.29
	Quiet breathing and spontaneous speech	0.81	0.09	0.01*	0.24;1.39
T_e (sec)	Reading and spontaneous speech	0.02	0.29	1.00	-1.79;1.84
	Reading and counting	0.22	0.66	1.00	-3.88;4.34
	Counting and spontaneous speech	0.25	0.79	1.00	-4.17;5.21
	Quiet breathing and reading	1.51	0.10	0.00*	0.86;2.15
	Quiet breathing and counting	1.73	0.63	0.42*	-2.20;5.67
	Quiet breathing and spontaneous speech	1.48	0.24	0.05*	-0.04;3.01
%RC Insp	Reading and spontaneous speech	11.51	2.90	0.17	-6.61;29.63
	Reading and counting	11.98	1.83	0.04*	0.53;23.44
	Counting and spontaneous speech	0.47	2.69	1.00	-16.32;17.26
	Quiet breathing and reading	7.58	9.11	1.00	-49.21;64.39
	Quiet breathing and counting	19.57	9.97	0.86	-42.58;81.73
	Quiet breathing and spontaneous speech	19.10	8.05	0.59	-31.11;69.31
%AB Insp	Reading and spontaneous speech	11.48	2.87	0.16	-6.45;29.42
	Reading and counting	11.79	1.76	0.04*	0.81;22.77
	Counting and spontaneous speech	0.03	2.67	1.00	-16.34;16.94
	Quiet breathing and reading	8.09	9.27	1.00	-49.69;65.87
	Quiet breathing and counting	19.88	10.02	0.84	-42.56;82.32
	Quiet breathing and spontaneous speech	19.58	8.16	0.57	-31.31;70.47

*Starred results significant at the 0.05 alpha level

T_i= Inspiratory time (seconds), T_e= Expiratory time (seconds); %RCInsp = Regional contribution of the ribcage to the inspiration phase; %ABInsp = regional contribution of the abdomen to the inspiration phase.

Table 22 Results from the post hoc analysis: Pairwise comparisons between quiet breathing, reading counting and conversational speech in patients with bronchiectasis (n=4)

Based on the descriptive statistics in table 21, the counting task was associated with the shortest respiratory timing components (inspiration, expiratory and breathing cycle time), smallest magnitudes, smallest regional contributions of the ribcage and abdomen, and the fastest respiratory rate when compared with the reading and conversational speech task. The findings from the one way repeated measures ANOVA identified statistically significant differences for four breathing parameters, namely inspiration time ($F=43.39$, $DF=3$, $p=0.00$), expiration time ($F=4.68$, $df=3$, $p=0.03$), %RCInsp ($F=4.05$, $df=3$, $p=0.04$) and %ABInsp ($F=4.10$, $df=3$, $p=0.04$).

The results from the pair-wise post hoc analysis (table 22) revealed that respiratory timings (inspiration and expiration time) could differentiate between quiet breathing and each speech task. However, the differences between the speech tasks were less discriminating, as statistically significant differences were only identified between the reading and counting task for inspiration time, and the regional contribution of the ribcage and abdomen during the inspiration phase.

7.4.6 Characterising breathing and speech breathing patterns in patients with COPD

In total, fourteen patients with COPD were recruited in the sample. Due to a number of technical failures that occurred during the data collection phase, seven data sets could not be included in analysis (quiet breathing ($n=4$), reading ($n=1$), counting ($n=1$) and conversational speech ($n=1$), leaving 10 full data sets. Since ANOVA requires a full data set for analysis, this analysis was therefore based on 10 patients. Table 23 presents the descriptive statistics and results from the one way repeated measures ANOVA. This is followed by the post hoc analysis in table 24.

	Quiet breathing (n =10)	Reading (n =13)	Conversation (n =13)	Counting (n =13)	One way repeated measures ANOVA results		
					F	df	p
T _i (sec)	1.59±0.71	0.66±0.15	0.74±0.19	0.67±0.26	13.67	3 ¹	0.00*
T _e (sec)	2.36±0.86	2.99±0.66	3.73±1.23	3.57±1.95	4.19	1.36 ²	0.06
IM (a.u)	1.36±0.53	1.52±0.49	1.61±0.51	1.22±0.32	0.79	1.38 ²	0.43
EM (a.u)	1.37±0.54	1.51±0.47	1.60±0.52	1.26±0.33	0.77	1.31 ²	0.44
T _{tot} (sec)	3.99±1.58	3.66±0.74	4.51±1.40	4.27±1.92	1.49	1.22 ²	0.26
RR (bpm)	16.90±5.41	16.95±2.99	14.35±3.51	16.09±4.98	1.17	1.19 ²	0.32
%RC Ins	60.55±11.65	65.61±10.29	63.33±12.55	59.78±11.28	1.66	3 ¹	0.19
%AB Ins	38.84±11.81	34.23±10.29	36.46±12.51	39.96±11.26	1.64	3 ¹	0.20
%RC Exp	65.00±11.81	65.62±15.84	62.61±12.48	60.33±11.74	0.47	3 ¹	0.70
%AB Exp	40.72±12.70	34.35±15.69	37.52±12.25	39.41±11.77	0.43	3 ¹	0.72

*Starred results significant at the 0.05 alpha level; ¹Sphericity assumed; ²Greenhouse-Geisser.

T_i (sec) = Inspiration time (seconds); T_e (sec) = expiration time (seconds); IM (a.u) = inspiration magnitude (arbitrary units); EM (a.u) = Expiration magnitude (arbitrary units); T_{tot} (sec) = breathing cycle time (seconds); RR (bpm) = respiratory rate (breaths per minute); %RC Insp = Ribcage percentage contribution to inspiration; %AB Insp = Abdominal percentage contribution to inspiration; %RC Exp = Ribcage percentage contribution to expiration; %AB Exp = Abdominal percentage contribution to expiration; DF = Degrees of Freedom.

Table 23 Breathing and speech breathing parameters in patients with COPD during quiet breathing reading, counting and conversational speech: Descriptive statistics and results from the one way repeated measures ANOVA (n=10)

	Paired comparison	Mean difference	Standard error of the mean difference	p Value	95% Confidence interval of the mean difference Upper bound; lower bound
T _i (sec)	Reading and conversational speech	0.04	0.09	1.00	-0.33;0.42
	Reading and counting	0.04	0.05	1.00	-0.27;0.17
	Counting and conversational speech	0.00	0.12	1.00	-0.48;0.48
	Quiet breathing and reading	0.78	0.17	0.02*	0.10;1.46
	Quiet breathing and counting	0.73	0.16	0.02*	0.10;1.37
	Quiet breathing and conversational speech	0.74	0.19	0.05	-0.02;1.50

*Starred results significant at the 0.05 alpha level

T_i= Inspiration time (seconds)

Table 24 Results from the post hoc analysis: Pairwise comparisons between quiet breathing, reading counting and conversational speech in patients with COPD (n=10)

Some suggestion of possible task specificity in patients with COPD was initially observed. The linguistically unconstrained task (conversational speech) seemed to be associated with the longest respiratory timing components, greatest magnitudes and slowest respiratory rate. The regional contributions of the ribcage and abdomen seemed to be the smallest during the counting task. However, while the results from the one way repeated measures ANOVA revealed differences to be significant for inspiration time ($F=13.67$, $df=3$, $p=0.00$), the post hoc analysis demonstrated that these differences were only significant between quiet breathing and speech (counting ($p=0.02$) and reading ($p=0.02$)), but not between any of the speech tasks. There was therefore no evidence of speech task specificity within the COPD sample.

7.4.7 Characterising breathing and speech breathing patterns in patients with chronic respiratory disease – pooled data from COPD and bronchiectasis (pooled patients with CRD)

A decision was taken to pool the data from patients with COPD and bronchiectasis in to one group on the basis of their similarities in age and available spirometry (see table 18 for comparative analysis). The pooled COPD and bronchiectasis group will now be **referred to as ‘pooled patients with CRD’**.

Descriptive analysis

The number of participants included in each analysis varies across the tasks. Several data sets had to be removed due to technical failures during the data collection process. The number of patient data sets included in each task has varied accordingly: quiet breathing = 14, reading = 19, counting = 19, conversation = 19. A detailed description of missing data is presented later in section 7.6.8.

On average, the quiet breathing task was characterised by having the longest inspiratory phase, and the greatest $T_i/T_{tot}\%$. Within the speech tasks, conversation was associated with the longest breathing cycles, as participants had the longest inspiration and expiration phases. The counting task appeared to place the greatest respiratory demand on speech breathing, as this task was associated with the fastest respiratory rate and the smallest breath sizes from all tasks. When examining the percentage ribcage and abdominal contributions

to inspiration and expiration, tidal breathing was dominated by ribcage displacement during all tasks.

7.4.8 Analysis of variance – comparison between breathing and speech tasks in pooled patients with CRD

After pooling the COPD and bronchiectasis data, breathing and speech breathing parameters were compared among the four tasks to determine whether breathing and speech breathing patterns were ‘task specific’ for this pooled group. All data were found to be normally distributed using the Shapiro-Wilk test, and a one way repeated measures ANOVA was used to compare each breathing parameter among the various tasks (quiet breathing, reading, conversation and counting). The Greenhouse Geisser correction was used when the assumptions of Mauchly’s Test of Sphericity were violated. Table 25 presents these results for the group. Since ANOVA requires a full data set for analysis, data from 14 participants were included in this analysis, as there were missing data from six participants during each of the tasks. Any significant results were followed up by post hoc test using the Bonferroni correction for multiple comparisons which is presented in table 26.

	Quiet breathing (n = 14)	Reading (n = 19)	Conversation (n = 19)	Counting (n = 19)	One way repeated measures ANOVA		
					F	df	p
T _i (sec)	1.54±0.60	0.65±0.13	0.72±0.17	0.64±0.24	29.14 ²	1.24	0.00*
Ti/Ttot (%)	39.58	16.88	16.25	15.38	-	-	-
T _e (sec)	2.31±0.80	3.17±0.71	3.68±1.09	3.48±1.79	6.74 ²	1.70	0.00*
IM (a.u)	1.30±0.49	1.42±0.49	1.91±0.65	1.14±0.29	1.29 ¹	3	0.28
EM (a.u)	1.31±0.49	1.41±0.48	1.87±0.63	1.17±0.30	1.17 ²	1.85	0.32
Ttot (sec)	3.89±1.39	3.85±0.77	4.43±1.22	4.16±1.60	1.41 ²	1.80	0.26
RR (bpm)	17.00±4.90	16.19±2.95	14.43±3.27	16.57±5.45	2.30 ²	1.72	0.12
%RC Ins	61.91±11.38	64.08±11.36	60.39±14.07	57.67±13.60	3.67 ²	1.64	0.05
%AB Ins	37.44±11.56	35.72±11.36	39.38±14.02	41.99±13.56	2.82 ²	1.56	0.09
%RC Exp	60.51±12.36	63.49±15.18	59.58±14.30	59.70±11.81	1.05 ¹	3	0.38
%Ab Exp	38.90±12.45	36.42±15.06	40.34±14.03	39.99±11.83	1.37 ¹	3	0.34

*Starred results significant at the 0.05 alpha level; ¹Sphericity assumed; ²Greenhouse Geiser; **TI (sec)** = Inspiration time (seconds); **Ti/Ttot%** = percentage of time spent on inspiration; **TE (sec)** = expiration time (sec); **IM (a.u)** = inspiration magnitude (arbitrary units); **EM (a.u)** = Expiration magnitude (arbitrary units); **Ttot (sec)** = breathing cycle time (sec); **RR (bpm)** = respiratory rate (breaths per minute); **% RC Insp** = Ribcage percentage contribution to inspiration; **%AB Insp** = Abdominal percentage contribution to inspiration; **%RC Exp** = Ribcage percentage contribution to expiration; **%AB Exp** = Abdominal percentage contribution to expiration; **DF** = Degrees of Freedom;

Table 25 Breathing and speech breathing parameters in pooled COPD and bronchiectasis data; Comparison between quiet breathing, reading, spontaneous speech and counting – results of the one way repeated measures ANOVA (n=14)

	Paired comparison	Mean difference	Standard error of the mean difference	p Value	95% Confidence interval of the mean difference	
					Lower	Upper
T_I (sec)	Reading and spontaneous speech	0.07	0.04	0.09	-0.01;0.16	
	Reading and counting	0.001	0.61	0.98	-0.12;0.13	
	Counting and spontaneous speech	0.07	0.07	0.37	-0.09;0.24	
	Quiet breathing and reading	0.87	0.15	0.00*	0.55;1.20	
	Quiet breathing and counting	0.87	0.11	0.00*	0.63;1.12	
	Quiet breathing and spontaneous speech	0.80	0.16	0.00*	0.44;1.16	
T_E (sec)	Reading and spontaneous speech	0.65	0.25	0.05	0.10;1.19	
	Reading and counting	0.43	0.39	0.28	-0.41;1.28	
	Counting and spontaneous speech	0.21	0.37	0.57	-0.59;1.02	
	Quiet breathing and reading	0.92	0.30	0.01*	0.26;1.58	
	Quiet breathing and counting	1.36	0.56	0.03*	0.14;2.58	
	Quiet breathing and spontaneous speech	1.57	0.31	0.00*	0.89;2.26	

*Starred results significant at the 0.05 alpha level (2 tailed).

T_I (sec) = Inspiration time (seconds); T_E (sec) = expiration time (sec)

Table 26 Results from the post hoc analysis: Pairwise comparisons between quiet breathing, reading counting and conversational speech in pooled patients with chronic respiratory disease (n=14)

7.4.9 Post hoc analysis for pooled patients with chronic respiratory disease

The findings from the one way repeated measures ANOVA (table 25) identified statistically significant differences among the tasks for two breathing parameters, namely, inspiration ($F = 29.14$, $df = 1.24$, $p = 0.00$) and expiration time ($F = 6.74$, $df = 1.40$, $p = 0.00$). When these findings were followed up by post hoc tests (table 26), the results demonstrated that these parameters were only significantly different between quiet breathing and speech tasks, **but not between the different speech tasks**. Therefore, there is no evidence within this sample to suggest that patients with chronic respiratory disease produce ‘task specific’ breathing patterns.

7.4.10 Summary of section four

Visual inspection of the breathing parameters produced in self-reported asthma, bronchiectasis, COPD and the pooled patients with CRD revealed similar breathing patterns as found for healthy adults during the various breathing and speech tasks; the linguistically unconstrained speech task (conversational speech) was associated with the longest respiratory timing components, greatest magnitudes and the slowest respiratory rates. However, there was limited evidence that the differences between the speech tasks were task specific when examined according to self-reported asthma, and bronchiectasis, and no evidence to suggest that patients with COPD or the pooled sample with chronic respiratory disease produce task specific speech breathing patterns. The following table presents a summary of findings with respect to the hypotheses described in section 7.4.1.

Table 27 Summary of section 7.4

Hypothesis	Summary of findings	Rejected/partially supported/supported?
HP4a	<ul style="list-style-type: none"> • In self-reported asthma, no statistically significant differences were identified amongst the tasks, apart from inspiration time. • These differences were significant for every comparison between quiet breathing task and each speech task. • the differences between the speech tasks were found to be significant between describing and conversational speech. 	Partially supported
HP4b	<ul style="list-style-type: none"> • In bronchiectasis, four breathing parameters were found to be significant, namely; inspiration and expiration time and the regional contribution of the ribcage and abdomen to inspiration. • for inspiration and expiration time, differences between the quiet breathing and each speech task was found to be significant, however the differences between the speech tasks were less discriminating. • The differences for %RCInsp and %ABInsp were significant between describing and conversational speech. 	Partially supported
HP4c	<ul style="list-style-type: none"> • In COPD, no statistically significant differences were identified amongst the tasks, apart from inspiration time. • These differences were significant between quiet breathing and speech • No statistically significant differences were identified between the speech tasks 	Partially supported
HP4d	<ul style="list-style-type: none"> • In the pooled patients with CRD, two breathing parameters were found to be statistically significant, namely inspiration and expiration time. • These differences were found to be significant between quiet breathing and each of the speech tasks. • No statistically significant differences were identified between the speech tasks 	Partially supported

7.5 Section Five

Breathing and speech breathing patterns: Comparisons between groups

In the previous sections, breathing patterns were explored and characterised for healthy adults and patients with chronic respiratory diseases during various breathing and speech tasks. A comparative analysis will now be presented, where breathing and speech breathing patterns have been compared as follows:

1. Healthy young adults *versus* healthy older adults
2. Healthy young adults *versus* young adults with a self-reported history of asthma
3. Patients with a diagnosis of COPD *versus* patients with a diagnosis of bronchiectasis
4. Older patients CRD *versus* healthy older adults

7.5.1 Rationale for comparative analysis

The comparative analysis has been performed a) to look further at the potential influence of age on speech breathing patterns and b) to explore any differences in speech breathing characteristics between health and chronic respiratory disease. If speech breathing pattern analysis is to be considered as monitor of respiratory health over time, there is a need to establish whether the measure can be used to detect any significant differences between health and disease, and to determine whether the type of speech influences the detection of the differences. Studies comparing speech breathing patterns in different age groups have not yet established any clear differences between groups, and the methods used to obtain these data are now considered to be technologically dated (Hoit & Hixon 1987; Hoit et al. 1990). Only two previous studies have performed comparative analyses between healthy adults and patients with chronic respiratory disease. (Loudon et al. 1988; Lee et al. 1993). These studies compared the lung volumes, flow rates and respiratory timing components between healthy adults and patients with asthma (Loudon et al. 1988), sarcoidosis, and emphysema (COPD) (Lee et al. 1993). However, any difference in speech breathing patterns between health and chronic respiratory disease remains poorly understood. Age has not previously been addressed as a

potential confounding factor (Hoit & Hixon 1987; Hoit et al. 1990). No-one has previously explored the regional contributions of the ribcage and abdomen during speech breathing. The authors' conclusion that speech breathing pattern analysis could differentiate between health and disease, as well as between different diagnostic groups, was based on the analysis of only two types of speech, namely counting and conversation, where a total of 20 breathing cycles were subjectively selected for analysis (Loudon et al. 1988; Lee et al. 1993).

The novel aspects of this research are: 1) analysis of the regional contributions of the ribcage and abdomen, 2) using a wider range of tasks for analysis: to include reading and quiet breathing (as well as the counting and conversation used by previous researchers), 3) inclusion of bronchiectasis patients (as well as asthma and COPD).

7.5.2 Comparative analysis: Justification and selection of breathing parameters

Within the analysis so far, breathing patterns have been characterised and analysed for all of the ten breathing parameters that were extracted from the raw data files to provide full descriptive summaries. The aim of this next section was to perform comparative analyses between the various groups previously outlined. Since independent t tests were used to test for any statistically significant differences between the groups, a decision was made to reduce the parameter number for the pair-wise comparative analysis in an attempt to reduce the probability of type one errors (Lieberman & Cunningham 2009). Since 10 tests were being performed for each task, the type one error rate could increase to 50%, which was considered to be unacceptable. While the Bonferroni adjustment for multiple comparisons accounts for this error rate, the procedure ignores any dependencies among the data and becomes too conservative with increasing tests (Bender & Lange 1999; Lieberman & Cunningham 2009). Therefore, reducing the number of tests being performed would reduce the type one error rate, without being too conservative.

In addition to wishing to reduce the number of comparisons being performed, it was felt that some of the breathing pattern parameters were interrelated, or reciprocals of each other. So a decision was taken to conduct the comparative analyses based on only four breathing parameters representing respiratory timings, magnitudes and regional contributions of the rib cage and abdomen.

The parameters selected for the comparative analysis were: **respiratory rate, expiration time (T_E), expiration magnitude (IM) and the percentage contribution of the rib cage to expiration (%RCExp)**. If speech breathing pattern analysis is to become incorporated into the routine monitoring of respiratory health, reducing the number of parameters needed for clinical interpretation could have a better clinical acceptability. A Justification for the parameters selected will now be provided. A justification for the selection of the breathing parameters used for the comparative analyses will now be presented.

Parameter selection justification

Respiratory timing parameters

Respiratory rate measured as breaths per minute (bpm) is a standard measure for assessing clinical status and has therefore been included (Kennedy 2007).

Expiratory time was selected because speech production is typically formed in the expiratory phase of the respiratory cycle (Hoit et al. 1989; Lee et al. 1993; Winkworth et al. 1994). Speech breathing patterns are characterised by having a long expiration, and a short inspiration phase, to minimise the silences during speech production and extend the time available for spoken speech (Winkworth et al. 1995; Binazzi et al. 2006). It is the extended expiratory phase that predominantly determines both respiratory rate and the breathing cycle time, as the inspiratory phase produced during speech is too short relatively to have a significant influence on these parameters (Winkworth et al. 1995). In patients with COPD, expiratory flow limitation is the hallmark of the disease (GOLD 2014), which is associated with the duration of the expiration phase, but not the inspiratory phase. The advantage of analysing the long expiratory phase is also concerned with measurement error. Measurement error would have a greater relative impact on shorter measurement periods. A decision was therefore made to use expiratory time to represent breathing cycle time. In previous research expiratory time was found to predict patient group membership (Lee et al. 1993)

Respiratory magnitudes

It is generally accepted that the volume of air breathed in is approximately equal to the volume of air breathed out (Adams et al. 1993b). Respiratory magnitudes measured by RIP bands were also reflective of this process since the data concerning inspiratory and expiratory magnitudes from all three studies showed

equivalence (inspiratory magnitude = expiratory magnitude in all data sets). A decision was therefore made to select expiratory magnitude for comparative purposes to maintain consistency with the use of expiratory time.

Regional contributions of the ribcage and abdomen

The relative contributions of the sections of chest wall to each breath sum to 100%. The movement of each RIP band (thoracic and abdominal) reflects the regional contribution of the ribcage and abdomen to this total movement. An increase in the proportion of ribcage movement is therefore associated with an equal reduction in the proportion of abdominal movement. As a result of this inter-dependency a decision was made to analyse only the contribution of the ribcage to total movement during the expiratory phase, for comparative purposes.

In summary, due to the increased probability of type one errors associated with multiple comparisons, and the interdependencies among the breathing parameters, a decision was taken to reduce the total number of parameters analysed during the comparative analysis. For characterisation and descriptive purposes, the complete breathing pattern profile using all 10 extracted parameters has been presented for healthy older adults and patients with chronic respiratory disease. The reduced parameter set has been used only for this comparative between group analysis.

7.5.3 Aims, Research questions and Hypotheses

Aims:

1. To compare breathing and speech breathing patterns between groups (healthy young vs healthy older; healthy young vs self-reported asthma; COPD vs bronchiectasis; healthy older vs pooled patients with CRD).
2. To determine whether the type of speech influences the detection of any differences between health and disease.

Research questions:

1. Can breathing and speech breathing pattern analysis significantly differentiate between groups?

2. What breathing/speech breathing task is the most useful for highlighting the differences between health and CRD?

Hypotheses will be presented individually according to each comparative analysis and will be summarised separately at the end of each subsection.

7.5.4 Healthy young adults versus healthy older adults

Breathing and speech breathing patterns were compared between the data obtained from healthy young adults during study one (mean age 33.7 ± 12.85 years) and healthy older adults in study two (mean age 66.90 ± 8.49). Since the average age difference was 33.2 years, it was considered important to further examine the influence of age on breathing and speech breathing patterns in healthy adults.

7.5.4.1 Hypotheses developed after data collection:

HP5a.1 There is a statistically significant difference in **mean expiratory time** (T_E) between healthy young and healthy older adults during quiet breathing, reading, and conversational speech.

HP5b.1 There is a statistically significant difference in **mean expiratory magnitude** (EM) between healthy young and healthy older adults during a quiet breathing, reading, and conversational speech task

HP5c.1 There is a statistically significant difference in **mean respiratory rate** (RR) between healthy young and healthy older adults during a quiet breathing, reading, and conversational speech task

HP5d.1 There is a statistically significant difference in **mean %RCExp** between healthy young and healthy older adults during a quiet breathing, reading, and conversational speech task.

Independent sample t tests adjusted via Bonferroni corrections were used to compare breathing and speech breathing parameters between healthy young and healthy older adults, as data from both groups were found to be normally distributed when examined using the Shapiro-Wilk test. Since a decision was made to remove the describing task from the second study (see section 8.1.1 for justification), comparisons between groups could only be performed during the quiet breathing, reading and conversational speech task. The next section

presents the results from the independent sample t tests where healthy young and healthy older adults were compared according to respiratory rate, expiration time, expiration magnitude and the regional contribution of the rib cage to the expiration phase (%RC Exp), during quiet breathing (table 28), reading (table 29) and conversational speech (table 30).

Quiet breathing task

Parameter	Healthy young (n=29)	Healthy old (n=20)	Mean diff.	t	df	p	95%CI
T _E (sec)	1.76±0.83	2.82±0.81	1.06	-4.42	47 ¹	0.00*	-1.54;-0.57
EM (a.u)	1.76±0.83	1.68±0.61	0.08	6.29	32.71 ²	0.00*	0.81;1.58
RR (bpm)	14.11±3.85	14.04±3.54	0.07	0.59	47 ¹	0.24	-2.11;2.24
%RC Exp	67.57±8.77	83.94±3.53	-16.37	-7.89	39.5 ¹	0.00*	-20.54;-12.59

Bonferroni corrections for multiple comparisons

*Starred results significant at the 0.05 alpha level; ¹Equal variances assumed; ²equal variances not assumed

T_E (sec) = expiration time (sec) EM (a.u) = Expiration magnitude (arbitrary units) RR (bpm) = respiratory rate (breaths per minute) %RC Exp = Ribcage percentage contribution to expiration

Table 28 Breathing and speech breathing parameters during quiet breathing in healthy young (n=29) and healthy older adults (n=20). Results from the independent sample t tests

Reading task

Parameter	Healthy young (n=29)	Healthy old (n=20)	Mean diff.	t	df	p	95% CI of the mean difference
T _E (sec)	3.58±0.79	3.86±0.84	0.28	-1.17	47 ¹	1 ^{NB}	-0.75;0.19
EM (a.u)	1.55±0.63	1.44±0.42	0.11	6.66	36.35 ²	0.00*	0.68;1.27
RR (bpm)	14.93±2.89	14.03±3.00	0.09	1.05	47 ¹	1 ^{NB}	-0.81;2.61
%RC Exp	64.60±8.06	83.56±3.56	18.96	-7.67	37.42 ²	0.00*	22.76;13.31

Bonferroni corrections for multiple comparisons

*Starred results significant at the 0.05 alpha level; ¹Equal variances assumed; ²equal variances not assumed

^{NB} p value capped at 1 one if p > 1 following Bonferroni corrections for multiple comparisons T_E (sec) = expiration time (sec) EM (a.u) = Expiration magnitude (arbitrary units) RR (bpm) = respiratory rate (breaths per minute) %RC Exp = Ribcage percentage contribution to expiration

Table 29 Breathing and speech breathing parameters during a reading task in healthy young (n=29) and healthy older adults (n=20). Results from the independent sample t tests

Conversational speech task

Parameter	Healthy young (n=29)	Healthy old (n=20)	Mean diff.	t	df	p	95% CI of the mean diff.
T _E (sec)	4.24±1.08	4.70±1.11	0.46	-0.52	47 ¹	1 ^{NB}	-0.82;0.48
EM (a.u)	1.96±0.70	1.50±0.63	0.46	8.91	40.05 ₂	0.00*	0.97;1.64
RR (bpm)	12.11±2.68	11.70±2.64	0.41	0.53	47 ¹	1 ^{NB}	-1.14;1.97
%RC Exp	64.82±9.23	83.38±3.84	18.56	-9.67	40.09 ²	0.00*	-22.96;-14.15

Bonferroni corrections for multiple comparisons

*Starred results significant at the 0.05 alpha level

^{NB} p value capped at 1 one if p > 1 following Bonferroni corrections for multiple comparisons

TE (sec) = expiration time (sec) EM (a.u) = Expiration magnitude (arbitrary units) RR (bpm) = respiratory rate (breaths per minute) %RC Exp = Ribcage percentage contribution to expiration; ¹Equal variances assumed; ²equal variances not assumed

Table 30 Breathing and speech breathing parameters during conversational speech task in healthy young (n=29) and healthy older adults (n=20). Results from the independent sample t tests

During the quiet breathing task, healthy older adults were found to have a significantly longer expiratory time ($t = 4.48$, $df=47$, $p=0.00$), smaller expiratory magnitude ($t=6.29$, $df=32.71$, $p=0.00$) and a greater ribcage contribution during expiration ($t= 7.89$, $df=39.5$, $p=0.00$). On average, healthy older adults had a faster respiratory rate, although the differences were not found to be statistically significant during the quiet breathing task ($t=0.59$, $df=47$, $p=0.00$).

The same pattern of difference was also observed during the reading and conversational speech task for each parameter, however the differences were only found to be statistically significant for expiration magnitude and %RC exp.

Table 31 presents a summary of findings with respect to the hypothesis described in section 7.5.4.1.

Table 31 Summary of section 7.5.4

Hypotheses	Summary of findings	Rejected/partially supported/supported?
HP5a.1	<ul style="list-style-type: none"> • Mean expiratory time was significantly longer in the healthy older group during the quiet breathing task. • No statistically significant differences were detected for expiratory time during the speech tasks. 	Partially supported
HP5b.1	<ul style="list-style-type: none"> • Mean expiratory magnitude was found to be significantly lower in the healthy older group. • These significant differences were consistently identified during every breathing and speech task examined. 	Supported
HP5c.1	<ul style="list-style-type: none"> • No statistically significant differences were identified between the two groups for respiratory rate. 	Rejected
HP5d.1	<ul style="list-style-type: none"> • %RCEp was found to be significantly greater in the healthy older group. • These significant differences were consistently identified during every breathing and speech task examined. 	Supported

7.5.5 Healthy young adults versus young adults with a self-reported history of asthma

A comparative analysis was performed between healthy young adults (n=29) (mean age 33.7±12.85) and adults who reported a history of asthma (n=11) (mean age 28.55±6.15) in order to determine whether there was any statistically significant differences between the two groups.

7.5.5.1 Hypotheses developed after data collection:

HP5a.2 There is a statistically significant difference in **mean expiratory time** (T_E) between healthy young and adults with self-reported asthma during quiet breathing, reading, describing and conversational speech.

HP5b.2 There is a statistically significant difference in **mean expiratory magnitude** (EM) between healthy young and adults with self-reported asthma during quiet breathing, reading, describing and conversational speech task.

HP5c.2 There is a statistically significant difference in **mean respiratory rate** (RR) between healthy young and adults who reported a history of asthma during a quiet breathing, reading, describing and conversational speech task.

HP5d.2 There is a statistically significant difference in **mean %RCExp** between healthy young and adults who reported a history of asthma during a quiet breathing, reading, describing and conversational speech task.

Independent t tests adjusted via Bonferroni corrections were used to test for any significant differences as the data from both groups were found to be normally distributed. The analysis has been presented according to the four breathing and speech tasks; quiet breathing (table 32), reading (table 33), describing (table 34) and conversational speech (table 35).

Quiet breathing task

Parameter	Healthy young (n=29)	Self-reported asthma (n=11)	Mean diff.	t	df	p	95%CI of the mean diff.
T_E (sec)	1.76±0.83	2.89±0.60	1.13	-4.08	38 ¹	0.00*	-1.68;-0.56
EM (a.u)	1.76±0.83	1.62±0.47	0.14	0.51	38 ¹	1 ^{NB}	-0.40;0.67
RR (bpm)	14.11±3.85	13.42±2.80	0.69	0.53	38 ¹	1 ^{NB}	-1.90;3.27
%RC Exp	67.57±8.77	62.95±5.34	4.62	1.62	38 ¹	0.44	-1.12;10.36

Bonferroni corrections for multiple comparisons

*Starred results significant at the 0.05 alpha level

^{NB} p value capped at 1 one if p >1 following Bonferroni corrections for multiple comparisons

T_E (sec) = expiration time (sec) EM (a.u) = Expiration magnitude (arbitrary units) RR (bpm) = respiratory rate (breaths per minute) %RC Exp = Ribcage percentage contribution to expiration; ¹Equal variances assumed; ²equal variances not assumed

Table 32 Breathing and speech breathing parameters during a quiet breathing task in healthy young adults (n=29) and adults who reported a history of asthma (n=11). Results from the independent sample t tests.

Reading task

Parameter	Healthy young (n=29)	Self-reported asthma (n=11)	Mean diff.	t	df	p	95% CI of the mean diff.
T _E (sec)	3.58±0.79	3.29±0.84	0.29	1.00	38 ¹	1 ^{NB}	-0.29;0.86
EM (a.u)	1.55±0.63	1.58±0.79	0.03	-0.15	38 ¹	1 ^{NB}	-0.52;0.44
RR (bpm)	14.93±2.89	16.40±3.58	1.47	1.12	38 ¹	0.72	-3.68;0.74
%RC Exp	64.60±8.06	62.48±6.81	2.12	0.77	38 ¹	1 ^{NB}	-3.43;7.68

Bonferroni corrections for multiple comparisons

*Starred results significant at the 0.05 alpha level

^{NB} p value capped at 1 one if p >1 following Bonferroni corrections for multiple comparisons

T_E (sec) = expiration time (sec) EM (a.u) = Expiration magnitude (arbitrary units) RR (bpm) = respiratory rate (breaths per minute) %RC Exp = Ribcage percentage contribution to expiration;¹Equal variances assumed; ²equal variances not assumed

Table 33 Breathing and speech breathing parameters during a reading task in healthy young adults (n=29) and adults who reported a history of asthma (n=11). Results from the independent sample t tests

Describing task

Parameter	Healthy young (n=29)	Self-reported asthma (n=11)	Mean diff.	t	df	p	95% CI of the mean difference
T _E (sec)	4.42±0.82	3.70±1.12	0.72	1.66	38 ¹	0.56	-0.11;1.19
EM (a.u)	1.84±0.68	1.99±0.76	0.15	-0.57	38 ¹	1 ^{NB}	-0.65;0.36
RR (bpm)	13.34±2.33	14.66±3.26	1.32	-2.33	38 ¹	0.08	-4.12;-0.29
%RC Exp	62.74±9.14	64.30±8.36	1.56	-0.49	38 ¹	1 ^{NB}	-0.97;4.84

Bonferroni corrections for multiple comparisons

*Starred results significant at the 0.05 alpha level

^{NB} p value capped at 1 one if p >1 following Bonferroni corrections for multiple comparisons

T_E (sec) = expiration time (sec) EM (a.u) = Expiration magnitude (arbitrary units) RR (bpm) = respiratory rate (breaths per minute) %RC Exp = Ribcage percentage contribution to expiration;¹Equal variances assumed; ²equal variances not assumed

Table 34 Breathing and speech breathing parameters during a describing task in healthy young adults (n=29) and adults who reported a history of asthma (n=11). Results from the independent sample t tests

Conversational speech task

Parameter	Healthy young (n=29)	Self-reported asthma (n=11)	Mean diff.	t	df	p	95% CI of the mean difference
T_E (sec)	4.24±1.08	3.84±0.76	0.70	1.92	38 ¹	0.24	-0.03;1.41
EM (a.u)	1.96±0.70	2.00±0.67	0.04	-0.13	38 ¹	1 ^{NB}	-0.53;0.46
RR (bpm)	12.11±2.68	14.21±2.34	2.11	-2.28	38 ¹	0.08	-3.96;-0.23
%RC Exp	64.82±9.23	64.39±5.22	0.43	0.14	38 ¹	1 ^{NB}	-5.56;6.42

Bonferroni corrections for multiple comparisons

*Starred results significant at the 0.05 alpha level

^{NB} p value capped at 1 one if p >1 following Bonferroni corrections for multiple comparisons

TE (sec) = expiration time (sec) EM (a.u) = Expiration magnitude (arbitrary units) RR (bpm) = respiratory rate (breaths per minute) %RC Exp = Ribcage percentage contribution to expiration; ¹Equal variances assumed; ²equal variances not assumed

Table 35 Breathing and speech breathing parameters during a conversational speech task in healthy young adults (n=29) and adults who reported a history of asthma (n=11). Results from the independent sample t tests

During the quiet breathing task, adults with self-reported asthma produced a significantly longer expiratory time (2.89 ± 0.60 sec) when compared to healthy young adults (1.76 ± 0.83 sec) ($t = -4.08$, $df = 38$, $p = 0.00$). In contrast, expiratory time was consistently found to be shorter during every speech task when compared to the healthy group, although none of these differences were found to be statistically significant. While no other statistically significant differences were observed between the groups for any parameter, a recurring pattern of difference was also observed for expiration magnitude and respiratory rate, where on average, as healthy adults consistently had a smaller expiratory magnitude and slower respiratory rate in comparison to adults with self-reported asthma.

Table 36 presents a summary of findings with respect to the hypothesis described in section 7.5.5.1.

Table 36 Summary of section 7.5.5

Hypotheses	Summary of findings	Rejected/partially supported/supported?
HP5a.2	<ul style="list-style-type: none"> • Expiratory time was found to be significantly longer in adults who reported a history of asthma during the quiet breathing task. • No significant differences were observed for expiration time during the speech tasks. 	Partially supported
HP5b.2	<ul style="list-style-type: none"> • No statistically significant differences were identified for expiratory magnitude during the quiet breathing or speech tasks. 	rejected
HP5c.2	<ul style="list-style-type: none"> • No statistically significant differences were identified for respiratory rate during the quiet breathing or speech tasks. 	rejected
HP5d.2	<ul style="list-style-type: none"> • No statistically significant differences were identified for %RCEp during the quiet breathing or speech tasks. 	rejected

7.5.6 Comparison between patients with a primary diagnosis of COPD and bronchiectasis

For reasons explained earlier (section 7.4.2), the self-reported asthma data have been excluded from this part of the analysis. Those data have already been compared to the healthy young adults. Before pooling the data from the COPD and bronchiectasis group, an analysis was conducted to look for any significant differences in speech breathing pattern between the two groups, because the underlying pathophysiology of COPD and bronchiectasis are known to be very different (Yoshida & Tuder 2007; Hacken N 2010). Analysis of demographic and anthropometric data had already indicated no differences in these variables – see section 7.4.2).

7.5.6.1 Hypotheses developed after data collection:

HP5a.3 There is a statistically significant difference in **mean expiratory time** (T_E) between patients with COPD and bronchiectasis during quiet breathing, reading, counting and conversational speech.

HP5b.3 There is a statistically significant difference in **mean expiratory magnitude** (EM) between patients with COPD and bronchiectasis during quiet breathing, reading, counting and conversational speech task.

HP5c.3 There is a statistically significant difference in **mean respiratory rate** (RR) between patients with COPD and bronchiectasis during a quiet breathing, reading, counting and conversational speech task.

HP5d.3 There is a statistically significant difference in **mean %RCExp** between patients with COPD and bronchiectasis during a quiet breathing, reading, counting and conversational speech task.

Respiratory rate, expiratory time, expiratory magnitude and the percentage contribution of the ribcage during expiration (%RCExp) were compared between patients with COPD and bronchiectasis using independent sample t tests adjusted via Bonferroni corrections during a quiet breathing, reading, spontaneous speech and counting task, as the data from both groups were found to be normally distributed when examined using the Shapiro-Wilk test. Descriptive statistics have been used to characterise of the overall breathing pattern profiles for both diagnostic groups table 37. This is followed by the comparative analysis with the results from the independent sample tests in table 38.

	<i>Quiet breathing task</i>		<i>Reading task</i>		<i>Conversation task</i>		<i>Counting task</i>	
	COPD (n=10)	BR (n=4)	COPD (n=13)	BR (n=6)	COPD (n=13)	BR (n=6)	COPD (n=13)	BR (n=6)
T_i (sec)	1.59±0.71	1.43±0.13	0.66±0.15	0.63±0.09	0.74±0.19	0.66±0.12	0.67±0.26	0.58±0.21
T_e (sec)	2.36±0.86	2.19±0.17	2.99±0.66	3.57±0.72	3.73±1.23	3.56±0.76	3.57±1.95	3.30±1.51
IM (a.u)	1.36±0.53	1.19±0.42	1.52±0.49	1.20±0.48	1.61±0.51	1.31±0.87	1.22±0.32	0.97±0.10
EM (a.u)	1.37±0.54	1.20±0.45	1.51±0.47	1.19±0.48	1.60±0.52	1.28±0.59	1.26±0.33	0.98±0.12
T_{tot} (sec)	3.99±1.58	3.64±0.84	3.66±0.74	4.26±0.74	4.51±1.40	4.26±0.79	4.27±1.92	3.92±1.66
RR (bpm)	16.90±5.41	17.25±4.01	16.95±2.99	14.55±2.2.7	14.35±3.51	14.62±2.99	16.09±4.98	17.60±6.74
%RC Ins	60.55±11.65	65.33±11.43	65.61±10.29	60.78±13.82	63.33±12.55	54.04±16.24	59.78±11.28	53.11±18.01
%AB Ins	38.84±11.81	33.92±11.74	34.23±10.29	38.94±13.87	36.46±12.51	45.70±16.18	39.96±11.26	46.41±18.00
%RC Exp	65.00±11.81	58.71±12.71	65.62±15.84	58.90±13.77	62.61±12.48	53.02±16.61	60.33±11.74	58.32±12.98
%Ab Exp	40.72±12.70	34.35±12.19	34.35±15.69	40.93±13.79	37.52±12.25	46.45±16.81	39.41±11.77	41.27±13.00

BR = Bronchiectasis; COPD = Chronic Obstructive Pulmonary Disease; T_i (sec) = Inspiration time (seconds); T_i/T_{tot}% = percentage of time spent on inspiration; T_e (sec) = expiration time (sec); IM (a.u) = inspiration magnitude (arbitrary units); EM (a.u) = Expiration magnitude (arbitrary units); T_{tot} (sec) = breathing cycle time (sec); RR (bpm) = respiratory rate (breaths per minute); %RC Insp = Ribcage percentage contribution to inspiration; %AB Insp = Abdominal percentage contribution to inspiration; %RC Exp = Ribcage percentage contribution to expiration; %AB Exp = Abdominal percentage contribution to expiration;

Table 37 Summary statistics: Breathing and speech breathing parameters according to primary diagnosis (COPD and bronchiectasis) during two minute quiet breathing, reading, counting and conversational speech task

	<i>Quiet breathing task</i>			<i>Reading task</i>			<i>Conversational speech task</i>			<i>Counting task</i>		
	COPD (n=10)	BR (n=4)	<i>p</i>	COPD (n=13)	BR (n=6)	<i>p</i>	COPD (n=13)	BR (n=6)	<i>p</i>	COPD (n=13)	BR (n=6)	<i>p</i>
T_e (sec)	2.36±0.86	2.19±0.17	0.73	2.99±0.66	3.57±0.72	0.10	3.73±1.23	3.56±0.76	0.75	3.57±1.95	3.30±1.51	0.76
EM (a.u)	1.37±0.54	1.20±0.45	0.54	1.51±0.47	1.19±0.48	0.20	1.60±0.52	1.28±0.59	0.32	1.26±0.33	0.98±0.12	0.05
RR (bmp)	16.90±5.41	17.25±4.01	0.90	16.95±2.99	14.55±2.2.7	0.10	14.35±3.51	14.62±2.99	0.87	16.09±4.98	17.60±6.74	0.59
%RCEp	65.00±11.81	58.71±12.71	0.41	65.62±15.84	58.90±13.77	0.38	62.61±12.48	53.02±16.61	0.18	60.33±11.74	58.32±12.98	0.74

Bonferonni correction for multiple comparisons. Results significant if $p < 0.05$

BR = Bronchiectasis; COPD = Chronic Obstructive Pulmonary Disease; TE (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); RR (bmp) = Respiratory rate; %RCEp = Percentage Ribcage contribution to expiration phase

Table 38 Comparison of breathing and speech breathing patterns between participants with a primary diagnosis of COPD and Bronchiectasis during a two minutes period of quiet breathing, reading, conversation and counting; Results of the independent t test

On average, patients with COPD seemed to have longer respiratory timing components (inspiration, expiration and breathing cycle duration), larger breaths (inspiration and expiration magnitude), and a slower respiratory rate during every task, than patients with bronchiectasis. The percentage ribcage contributions to inspiration and expiration also seemed to be smaller on average in patients with COPD. These observations were consistent for every task (see table 37). However, independent sample t tests (see table 38) showed no statistically significant differences for any breathing parameter when comparing between primary diagnosis of COPD and bronchiectasis ($p>0.05$). The lack of statistical significance was found to be consistent throughout each breathing and speech task (quiet breathing, reading, conversation and counting).

The following table presents a summary of findings with respect to the hypothesis described in section 7.5.6.1.

Table 39 Summary of section 7.5.6

Hypotheses	Summary of findings	Rejected/partially supported/supported?
HP5a.3	<ul style="list-style-type: none"> No statistically significant differences were identified for mean expiration time between COPD and bronchiectasis during any of the breathing and speech tasks examined. 	Rejected
HP5b.3	<ul style="list-style-type: none"> No statistically significant differences were identified for mean expiration magnitude between COPD and bronchiectasis during any of the breathing and speech tasks examined. 	Rejected
HP5c.3	<ul style="list-style-type: none"> No statistically significant differences were identified for mean respiratory rate between COPD and bronchiectasis during any of the breathing and speech tasks examined. 	Rejected
HP5d.3	<ul style="list-style-type: none"> No statistically significant differences were identified for mean %RCExp between COPD and bronchiectasis during any of the breathing and speech tasks examined. 	Rejected

7.5.7 Comparison between healthy older adults and participants with chronic respiratory disease (pooled patients with CRD)

In the previous sub section 7.5.6 it was revealed that speech breathing pattern analysis could not significantly differentiate between primary diagnosis of COPD and bronchiectasis during any of the breathing and speech tasks. Although some of the lung function data were missing, based on the available data both diagnostic groups had similar demography and lung function. Due to the lack of evidence for differences, it was considered appropriate to 'pool' the data from patients with COPD and bronchiectasis into one group (n=20) in order to increase the power of the sample for comparative analysis. The sample containing data from patients with a primary diagnosis of COPD and bronchiectasis will now be referred to as 'pooled patients with CRD'.

7.5.7.1 Hypotheses developed after data collection:

HP5a.4 There is a statistically significant difference in **mean expiratory time** (T_E) between healthy older adults and pooled patients with chronic respiratory disease during quiet breathing, reading, counting and conversational speech.

HP5b.4 There is a statistically significant difference in **mean expiratory magnitude** (EM) between healthy older adults and pooled patients with chronic respiratory disease during quiet breathing, reading, counting and conversational speech task.

HP5c.4 There is a statistically significant difference in **mean respiratory rate** (RR) between healthy older adults and pooled patients with chronic respiratory disease during a quiet breathing, reading, counting and conversational speech task.

HP5d.4 There is a statistically significant difference in **mean %RCExp** between healthy older adults and pooled patients with chronic respiratory disease during a quiet breathing, reading, counting and conversational speech task.

Breathing and speech breathing patterns were compared between healthy older adults and pooled patients with chronic respiratory disease. Independent sample t tests were used to test whether the differences between the ages in the two groups were statistically significant (table 40). Based on the results in table 40,

both groups had a sample size of 20 participants and the same ratio of males (n=8) to females (n=12). The average age difference between the two groups was 2.80 years, which was not found to be statistically significant (t=1.02, df=38, p=0.31).

The data collection procedures and RIP calibration procedures were identical so that any observed differences between the two groups could be attributed to a diagnosis of chronic respiratory disease, and not age, RIP calibration method or recording period.

	Sample size	sex	Age	Age comparison Mean diff.	t	df	p
Healthy older adults Mean±sd Range	20	M = 12 F = 8	66.90±8.49 (57 - 83)	2.80	1.02	38	0.31
CRD Patients Mean±sd Range	20	M = 12 F = 8	69.70±8.81 (51 - 84)				

M = Male, F= female

Table 40 Comparison between healthy older adults and pooled patients with CRD - results of the independent t test for age

The descriptive analysis comparing the ten breathing parameters between the two groups will firstly be presented (table 41). This will be followed by the comparative analysis, where independent sample t tests were used to test for statistically significant differences between the groups based on the following parameters; respiratory rate (RR), expiratory time (TE), expiratory magnitude (EM), Ribcage contribution to expiration (%RCExp) (table 42-45).

	<i>Quiet breathing task</i>			<i>Reading task</i>			<i>Conversational task</i>			<i>Counting task</i>		
	Healthy old n=20	Patient n=14	Diff	Healthy old n=20	Patient n=19	Diff	Healthy old n=20	Patient n=19	Diff	Healthy old n=20	Patient n=19	Diff
T_i (sec)	1.74±0.50	1.54±0.60	0.19	0.59±0.12	0.65±0.13	0.05	0.68±0.16	0.72±0.17	0.03	0.52±0.13	0.64±0.24	0.12
T_e (sec)	2.82±0.81	2.31±0.80	0.51	3.86±0.84	3.17±0.71	0.68	4.70±1.11	3.68±1.09	1.01	4.40±1.88	3.48±1.79	0.91
IM (a.u)	1.69±0.63	1.30±0.49	0.38	1.46±0.44	1.42±0.49	0.04	1.51±0.64	1.91±0.65	0.39	1.20±0.27	1.14±0.29	0.06
EM (a.u)	1.68±0.61	1.31±0.49	0.37	1.44±0.42	1.41±0.48	0.03	1.50±0.63	1.87±0.63	0.37	1.22±0.25	1.17±0.30	0.05
T_{tot} (sec)	4.58±1.28	3.89±1.39	0.68	4.44±0.93	3.85±0.77	0.59	5.54±1.29	4.43±1.22	1.00	4.96±2.06	4.16±1.80	0.80
RR (bpm)	14.04±3.54	17.00±4.90	2.95	14.03±3.00	16.19±2.95	2.15	11.70±2.64	14.43±3.27	2.73	13.62±5.01	16.57±5.45	2.60
%RCInsp.	84.40±3.31	61.91±11.38	22.48	82.93±3.56	64.08±11.36	18.84	82.99±4.35	60.39±14.07	22.59	82.42±6.12	57.67±13.60	24.74
%ABInsp.	12.95±3.29	37.44±11.56	24.48	15.38±3.84	35.72±11.36	20.33	14.97±4.41	39.38±14.02	24.04	15.72±6.54	41.99±13.56	26.27
%RCExp	83.94±3.53	60.51±12.36	23.42	83.56±3.56	63.49±15.18	20.70	83.38±3.84	59.58±14.30	23.79	84.85±7.47	59.70±11.81	25.15
%ABExp	13.42±3.69	38.90±12.45	25.48	14.66±4.20	36.42±15.06	21.76	14.75±3.75	40.34±14.03	25.58	14.04±7.54	39.99±11.83	25.95

Diff = Mean difference; **T_i (sec)** = Inspiration time (seconds); **T_e (sec)** = expiration time (sec); **IM (a.u)** = inspiration magnitude (arbitrary units); **EM (a.u)** = Expiration magnitude (arbitrary units); **T_{tot} (sec)** = breathing cycle time (sec); **RR (bpm)** = respiratory rate (breaths per minute); **%RCInsp** = Ribcage percentage contribution to inspiration; **%ABInsp** = Abdominal percentage contribution to inspiration; **%RC Exp** = Ribcage percentage contribution to expiration; **%ABExp** = Abdominal percentage contribution to expiration; **Diff** = Mean difference between the two groups.

Table 41 Descriptive analysis – comparison between healthy older adults (n=20) and pooled patients with chronic respiratory disease (n=19) during quite breathing, reading, conversation and counting

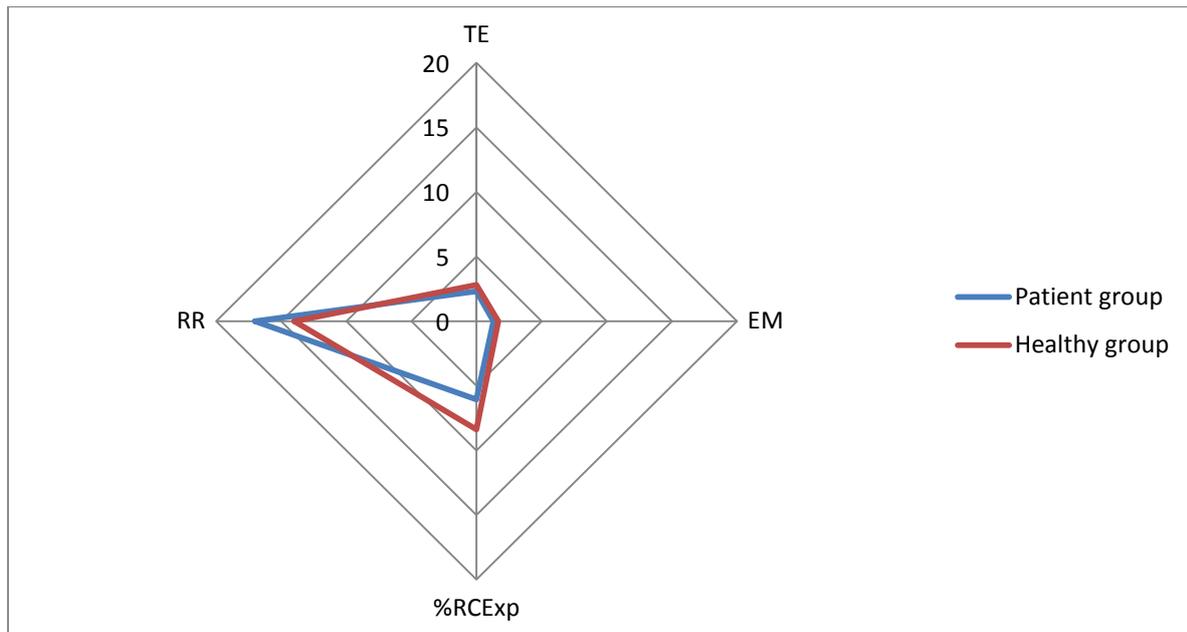
Descriptive analysis

On visual inspection, healthy older adults had longer respiratory timing components (inspiration and expiration time and breathing cycle time), took bigger breaths (inspiration and expiration magnitude) and had a slower respiratory rate in comparison to the pooled patients with chronic respiratory disease during the quiet breathing task. The regional contributions of the rib cage to inspiration and expiration phases appeared to be larger for the healthy older adults, and the abdominal contributions therefore appeared to be smaller during both phases. During the speech tasks (reading, conversation and counting), healthy older adults were consistently associated with having the shortest inspiratory and longest expiratory timing components, the longest breathing cycles and the slowest respiratory rates. Like quiet breathing, respiratory magnitudes and the regional contribution of the ribcage and abdomen to inspiratory and expiratory phases were greater in the healthy sample, where the abdominal contribution was proportionally smaller.

The breathing and speech breathing pattern profiles (based on rate, expiratory time, expiratory magnitude and the regional contribution of the ribcage to expiration) will now be compared between healthy older adults and the pooled patients with chronic respiratory disease. These profiles will firstly be visually compared using radar charts (figure 20-23), focusing on four parameters to represent timing, volume and movement (respiratory rate, expiratory time, expiratory magnitude and ribcage contribution). In these plots the %RCExp was divided by 10 for scaling purposes.

The differences between the two groups have then been tested using independent sample t tests adjusted via Bonferroni corrections (table 42-45), as both sets of data were normally distributed when assessed using the Shapiro-Wilk test. The confidence interval was set to 95% and a result was considered to be statistically significant if $p < 0.05$.

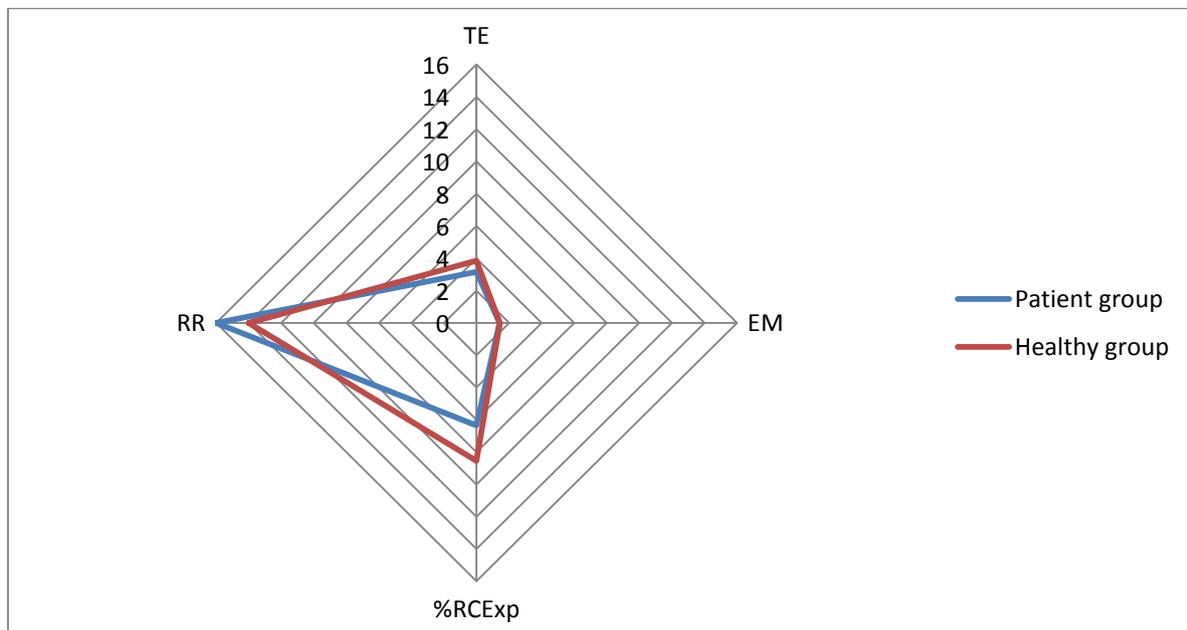
Quiet breathing task



RR = respiratory rate; TE (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCEp = Percentage ribcage contribution to expiration

Figure 20 Radar chart comparing the overall breathing pattern profile between healthy older adults (n=20) and pooled patients with CRD (n=14) during the quiet breathing task

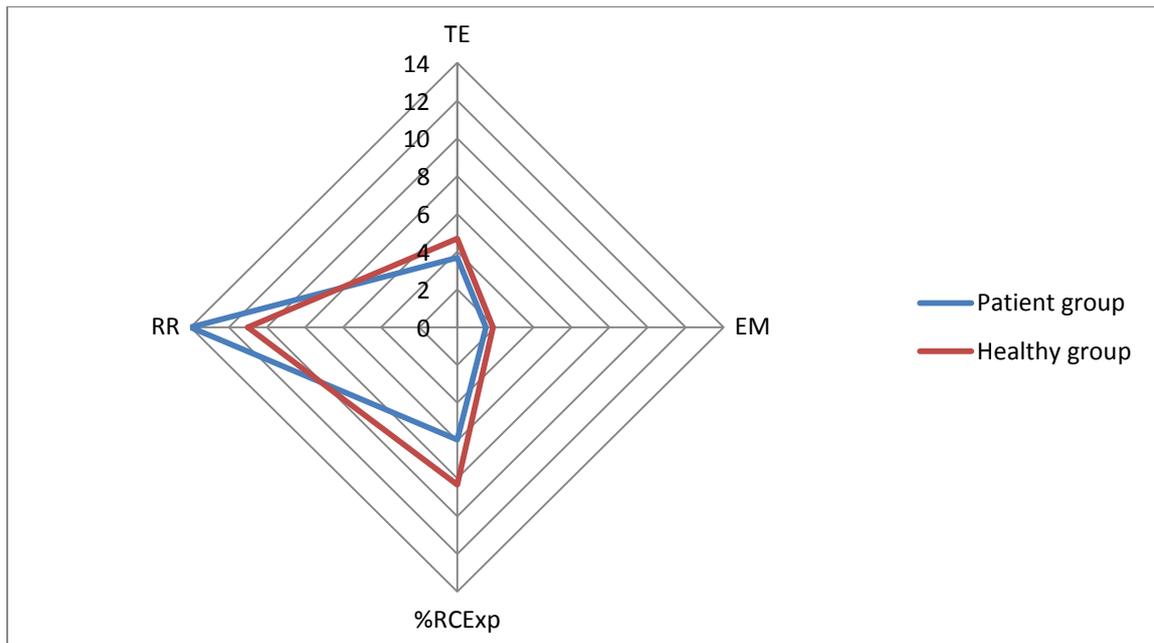
Reading task



RR = Respiratory rae; TE (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCEp = Percentage ribcage contribution to expiration

Figure 21 Radar chart comparing the overall breathing pattern profile between healthy older adults (n=20) and pooled patients CRD (n=19) during the reading task

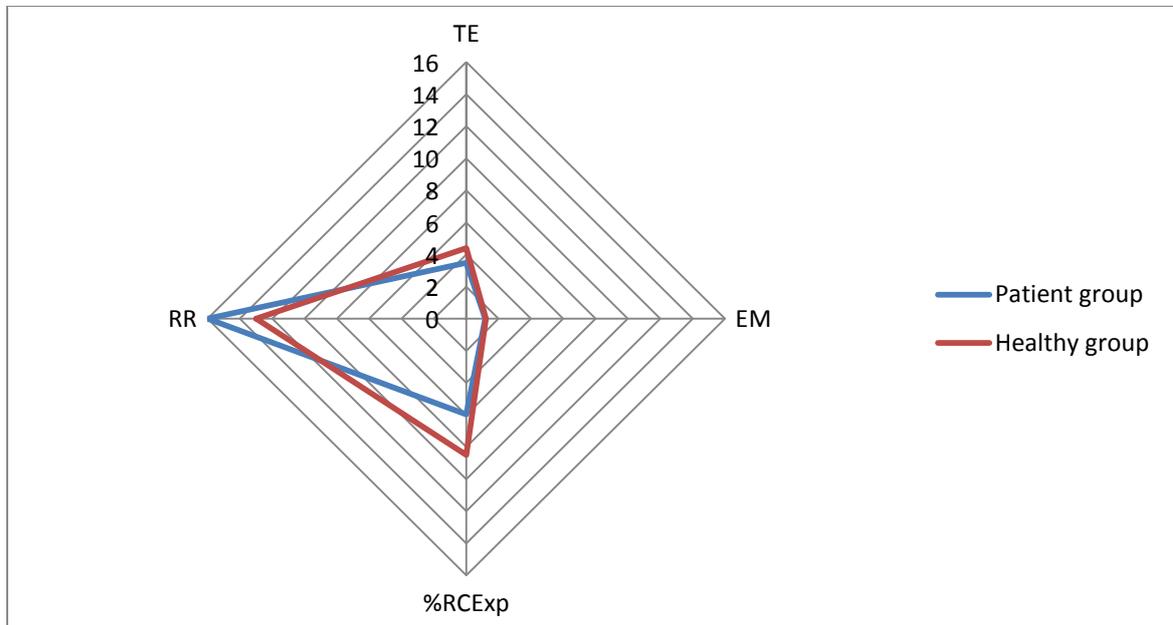
Conversational speech task



RR= Respiratory rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCEp = Percentage ribcage contribution to expiration

Figure 22 Radar chart comparing the overall breathing pattern profile between healthy older adults (n=20) and pooled patients CRD (n=19) during conversational speech

Counting task



RR= Respiratory rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCEp = Percentage ribcage contribution to expiration

Figure 23 Radar chart comparing the overall breathing pattern profile between healthy older adults (n=20) and pooled patients with C (n=19) during the counting task

Quiet breathing task

	Healthy older adults (n=20)	Pooled patients with CRD (n=14)	Mean difference	95%CI of mean difference		<i>t</i>	<i>df</i>	<i>p</i>
				Upper;	Lower			
T_E (sec)	2.82±0.81	2.31±0.80	0.51	-0.06;	1.08	1.82	32 ¹	0.28
EM (a.u)	1.68±0.61	1.31±0.49	0.37	-0.76;	0.02	-1.90	32 ¹	0.24
RR (bpm)	14.04±3.54	17.00±4.90	2.95	-5.89;	-0.01	-2.04	32 ¹	0.16
%RC Exp	83.94±3.53	60.51±12.36	23.42	16.16;	30.69	6.89	14.50 ²	0.00*

Bonferroni adjustment for multiple comparisons

*Starred results significant at the 0.05 alpha level (2-tailed)

RR=Respiratory Rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCExp = Percentage Ribcage contribution to expiration; DF = Degrees of Freedom; ¹equal variances assumed; ²equal variances not assumed

Table 42 Breathing parameters during quiet breathing; Comparison between healthy older adults (n= 20) and pooled patients (n=14) with chronic respiratory disease during quiet breathing – Results of the independent t tests

Reading task

	Healthy older adults (n=20)	Pooled patients with CRD (n=19)	Mean difference	95% CI of mean difference		t	df	p
				Upper	Lower			
T _E (sec)	3.86±0.84	3.17±0.71	0.86	0.17;1.19		2.71	37 ¹	0.04*
EM (a.u)	1.44±0.42	1.41±0.48	-0.03	-0.32;0.26		-0.21	37 ¹	1 ^{NB}
RR (bpm)	14.03±3.00	16.19±2.95	2.15	-4.08;-0.22		-2.25	37 ¹	0.12
%RC Exp	83.56±3.56	63.49±15.18	20.70	12.61;27.52		5.61	19.90 ²	0.00*

Bonferroni adjustment for multiple comparisons

*Starred results significant at the 0.05 alpha level (2-tailed)

^{NB} p value capped at 1 one if p > 1 following Bonferroni corrections for multiple comparisons

RR= Respiratory Rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCExp = Percentage Ribcage contribution to expiration; DF = Degrees of Freedom; ¹equal variances assumed; ²equal variances not assumed

Table 43 Breathing parameters during the reading task; Comparison between healthy older (n=20) adults and pooled patients with chronic respiratory disease (n=19) – Results of the independent sample t tests

Conversational speech task

	Healthy older adults (n=20)	Pooled patients with CRD (n=19)	95% CI of mean difference			t	df	p
			Mean difference	Upper	Lower			
T _E (sec)	4.70±1.11	3.68±1.90	1.01	0.28;1.17	2.82	37 ¹	0.00*	
EM (a.u)	1.50±0.63	1.87±0.63	-0.37	-0.78;0.03	-1.83	37 ¹	0.28	
RR (bpm)	11.70±2.64	14.43±3.27	-2.73	-4.66;-0.80	-2.87	37 ¹	0.00*	
%RC Exp	83.38±3.84	59.58±14.30	23.79	16.72;30.86	7.10	20.45 ¹	0.00*	

Bonferroni adjustment for multiple comparisons;

*Starred results significant at the 0.05 alpha level (2-tailed)

RR=Respiratory rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCExp = Percentage Ribcage contribution to expiration; DF = Degrees of Freedom; ¹equal variances assumed; ²equal variances not assumed

Table 44 Breathing parameters during the conversational speech task; Comparison between healthy older adults (n=20) and pooled patients with chronic respiratory disease (n=19) – Results of the independent t tests.

Counting task

	Healthy older (n=20)	Pooled patients with CRD (n=19)	Mean difference	95% CI of mean difference		t	df	p
				Upper	Lower			
T _E (sec)	4.40±1.88	3.48±1.79	0.91	-0.27;2.11		1.55	37 ¹	0.48
EM (a.u)	1.22±0.25	1.17±0.30	0.05	-0.13;0.24		0.54	37 ¹	1 ^{NB}
RR (bpm)	13.62±5.01	16.57±5.45	2.60	-5.99;0.79		-1.55	37 ¹	0.48
%RC Exp	84.85±7.47	59.70±11.81	25.15	6.29;43.37		2.85	22.92 ²	0.00*

Bonferroni adjustment for multiple comparisons

*Starred results significant at the 0.05 alpha level (2-tailed)

^{NB} p value capped at 1 one if p > 1 following Bonferroni corrections for multiple comparisons

RR= Respiratory Rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCExp = Percentage Ribcage contribution to expiration; DF = Degrees of Freedom; ¹equal variances assumed; ²equal variances not assumed

Table 45 **Breathing parameters during the counting task; Comparison between healthy older adults (n=20) and pooled patients with chronic respiratory disease (n=19) – Results of the independent sample t test**

Differences between healthy older adults and pooled patients CRD – results from the independent sample t tests

The results from the independent sample t tests revealed that the greatest number of significant differences between the two groups was observed during the conversational speech task, where expiratory time was found to be significantly shorter ($t=2.82$, $df=37$, $p=0.00$), respiratory rate was faster ($t=1.83$, $df=37$, $p=0.00$) and the %RCExp was smaller ($t=7.10$, $df=20.45$, $p=0.00$) in the patient group when compared to healthy older adults. No significant differences in expiration magnitude were detectable between healthy older adults and patients with chronic respiratory disease during any of the four tasks ($p>0.05$).

%RCExp was found to be significantly different between the two groups during every task ($p<0.05$), where the healthy older adults were found to have a significantly greater %RCExp when compared to the patient group. Figures 24 to 27 illustrate these data using boxplots. Within these boxplots, the middle horizontal line within each box represents the median. The 2 lines either side (limits) of the median signify the 25th (lower) and 75th (upper) percentile of the data. The 'limits' of the whiskers denote the 90th percentile and represent the extremities of the population. Outliers beyond the limits of the whiskers are indicated by a circle.

Quiet breathing task

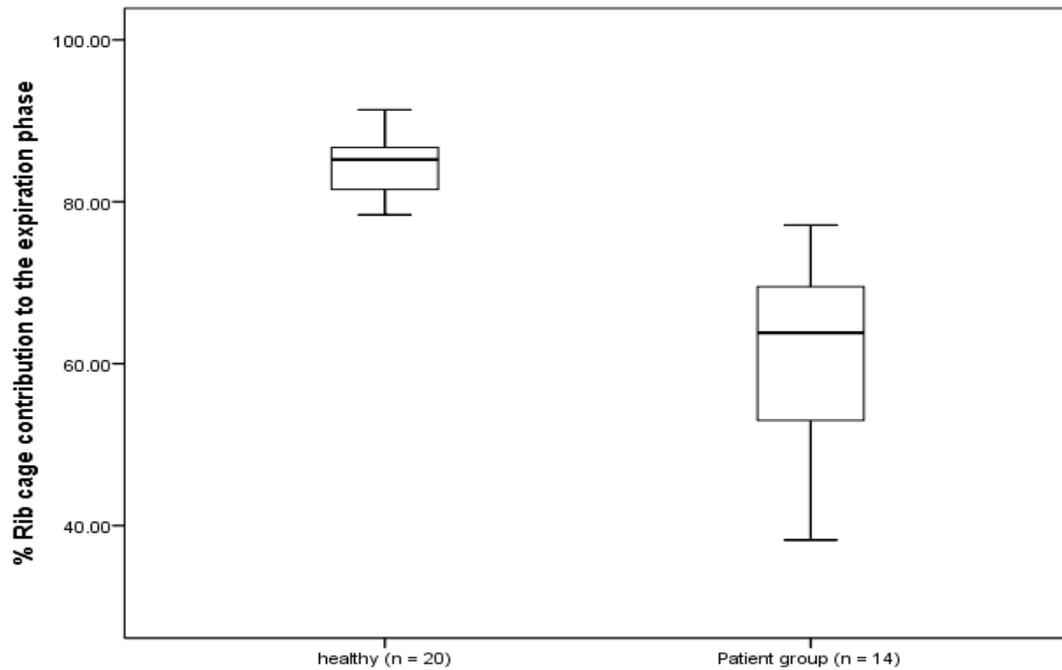


Figure 24 Boxplot graph comparing %RCExp between healthy older adults and pooled patients with chronic respiratory disease during the quiet breathing task

Reading task

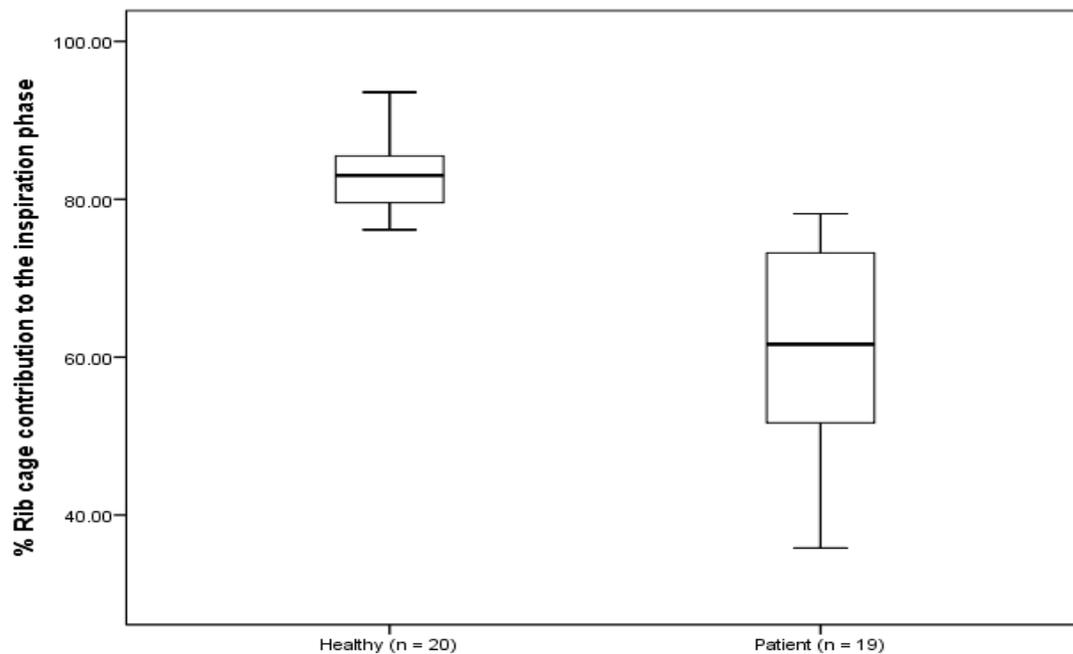


Figure 25 Boxplot graph comparing %RCExp between healthy older adults and pooled patients with chronic respiratory disease during the reading task

Conversational speech task

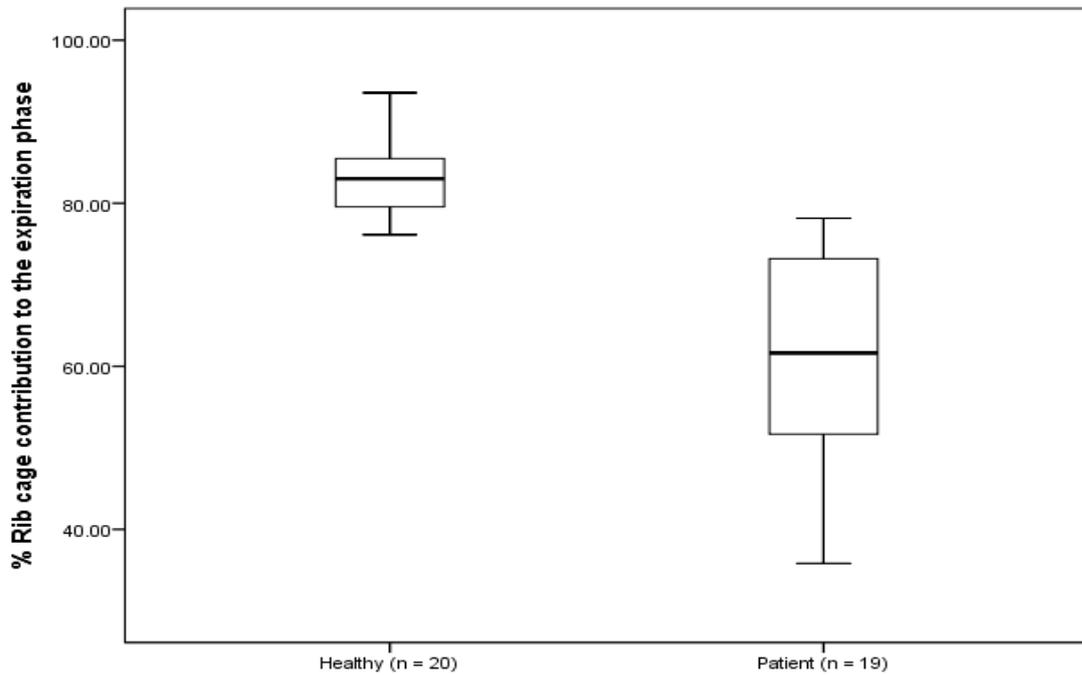


Figure 26 Boxplot graph comparing %RCExp between healthy older adults and pooled patients with chronic respiratory disease during the conversation task

Counting task

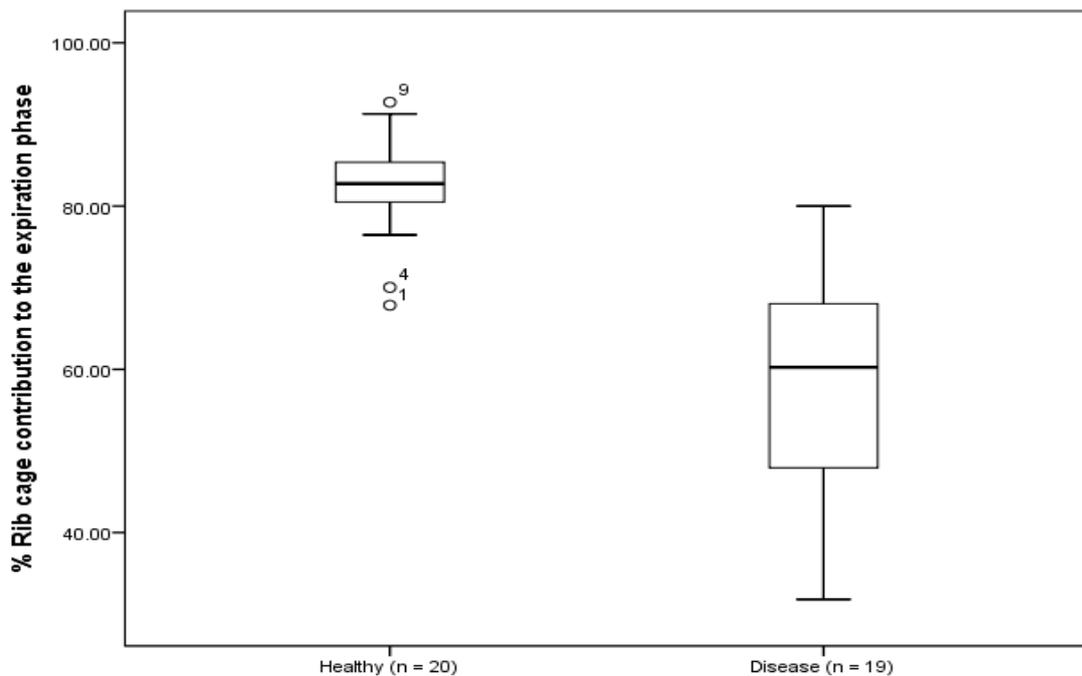


Figure 27 Boxplot graph comparing %RCExp between healthy older adults and pooled patients with chronic respiratory disease during the counting task

7.5.8 Breathing and speech breathing pattern variability: Comparison between healthy older adults and pooled patients with CRD

Breathing and speech breathing parameters were also analysed for their variability to determine how consistent the breathing parameters remained during the two minute recordings. The CoV% was calculated for each participant individually using the mean and SD during the two minute recordings. The results in table 46 present the mean CoV% for the whole group according to each breathing parameter and task.

The results presented in table 46 demonstrate that on average, the variability of speech breathing parameters during the quiet breathing task was consistently higher in the patient group when compared to healthy older adults, apart from expiration magnitude. This pattern of difference was not observed during any of the speech tasks. The variability of the rib cage contributions to inspiration and expiration in pooled patients with CRD was more than twice as high as healthy older adults during every breathing and speech task.

Table 46

Breathing and speech breathing pattern variability: comparison between healthy older adults and pooled patients with CRD during quiet breathing, reading, conversation and counting

	<i>Quiet breathing task</i>		<i>Reading task</i>		<i>Conversational speech task</i>		<i>Counting task</i>	
	<i>HO (n=20)</i>	<i>Patients (n=14)</i>	<i>HO (n=20)</i>	<i>Patients (n=19)</i>	<i>HO (n=20)</i>	<i>Patients (n=19)</i>	<i>HO (n=20)</i>	<i>Patients (n=19)</i>
T_I (Cov%)	22.83±5.28	33.81±20.89	35.34±9.37	34.78±6.98	39.92±9.17	36.58±7.08	29.40±10.84	38.52±11.31
T_E (Cov%)	26.23±10.75	29.61±13.11	50.50±7.71	45.90±11.73	49.22±11.72	52.13±9.65	49.93±7.37	56.72±19.66
IM (CoV%)	28.27±16.86	33.03±15.60	38.32±7.26	38.15±9.54	41.77±8.74	42.02±10.75	45.39±12.82	40.82±12.62
EM (CoV%)	33.19±23.47	32.40±13.96	51.47±10.42	45.90±11.73	51.75±11.39	47.45±10.41	69.55±28.30	49.14±13.17
T_{tot} (CoV%)	18.37±6.74	23.07±11.07	45.68±6.85	39.40±11.03	43.41±9.97	45.00±7.30	44.98±6.52	48.25±14.85
RR (bpm) (Cov%)	25.21±3.54	28.82±4.90	21.38±3.00	18.22±2.95	22.56±2.64	22.66±3.27	35.86±5.01	32.89±5.45
%RCInsp (CoV%)	3.05±1.55	15.31±13.12	5.10±1.46	14.54±7.38	5.83±2.52	20.35±12.66	6.10±3.46	16.31±10.18
%ABInsp (CoV%)	17.05±9.34	20.25±13.62	19.13±18.17	28.24±19.60	16.67±22.82	32.17±19.02	22.48±8.16	24.03±10.90
%RCExp (CoV%)	3.71±2.55	18.82±19.27	9.65±5.53	26.11±20.65	6.68±2.90	24.45±11.84	7.87±2.85	31.16±24.99
%ABExp (CoV%)	14.98±6.79	20.54±15.62	25.98±30.49	37.20±19.41	21.98±28.75	40.61±25.65	27.33±23.03	35.68±12.63

HO= Healthy older adults; CoV% = Coefficient of Variation expressed as a percentage; T_I(sec) = Inspiration time (seconds); T_E (sec) = expiration time (sec); IM (a.u) = inspiration magnitude (arbitrary units); EM (a.u) = Expiration magnitude (arbitrary); T_{tot} (sec) = breathing cycle time (sec); RR (bpm) = respiratory rate (breaths per minute); %RCInsp = Ribcage percentage contribution to inspiration; %ABInsp = Abdominal percentage contribution to inspiration; %RCExp = Ribcage percentage contribution to expiration; %ABExp = Abdominal percentage contribution to expiration

The following table presents a summary of findings with respect to the hypothesis described in section 7.5.7.1

Table 47 Summary of section 7.5.7

Hypothesis	Summary of findings	Rejected/partially supported/supported?
HP5a.4	<ul style="list-style-type: none"> The difference in expiratory time was found to be statistically significant between healthy older adults and pooled patients with chronic respiratory disease during the conversational speech task, but not for quiet breathing, counting or reading. 	Partially supported
HP5b.4	<ul style="list-style-type: none"> The differences in expiratory magnitude were not found to be statistically significant between healthy older adults and patients with chronic respiratory disease during any of the tasks. 	Rejected
HP5c.4	<ul style="list-style-type: none"> The differences in respiratory rate were found to be statistically significant between the groups during the conversational speech task, but not the reading, counting or quiet breathing task. 	Partially supported
HP5d.4	<ul style="list-style-type: none"> The differences in %RCEp were found to be statistically significant between older adults and patients with chronic respiratory disease during quiet breathing, reading, counting and conversation. 	Supported

7.5.9 Summary of section five

Comparisons between various groups have provided further insight into the influence of age on breathing and speech breathing patterns. Significant differences between age groups for expiration time and magnitude, and the %RCEp were observed during every breathing and speech task. No significant differences were identified during any of the speech tasks between healthy younger adults and adults who reported a history of asthma. The findings in section 7.5.6 provide no evidence to support the theory that speech breathing patterns are ‘disease specific’ as suggested by Lee *et al* (1993), as none of the breathing parameters were significantly different between patients with COPD and bronchiectasis during any of the tasks. However, differences in speech breathing pattern between chronic respiratory disease and an age-matched healthy group were identified during every task. In particular, expiration time

and %RCExp were significantly different between the two groups during reading and conversation, where the greatest number of differences was observed during the conversation task. %RCExp was found to be consistently greater in the healthy older group during every task ($p < 0.05$).

7.6 Section Six

Breathing and speech breathing patterns before, during and after a six week Pulmonary Rehabilitation programme in pooled patients with chronic respiratory disease

The final analysis in this research was conducted to explore whether speech breathing parameters have potential to respond to change. As described in section 6.3.1, an observational study was performed to collect data from patients with COPD and bronchiectasis before, during and after a clinical Pulmonary Rehabilitation programme.

Clinical data (exercise capacity and Modified Borg Scores) were analysed first to look for any evidence of change between the first and last day of PR, to evaluate the effect of PR within the sample. Breathing and speech breathing parameters have then been characterised for the patient group at three different time points (before, during and after PR). These parameters have been compared to determine whether there were any statistically significant differences among the time points. Breathing and speech breathing variability have also been examined at each time point, as well as the overall direction of change according to each breathing parameter. At the end there is a summary of the whole results chapter.

7.6.1 Aims, Research questions and Hypotheses

Aims:

1. To assess whether clinical measures (Modified Borg Scores and walking distance) changed following a six week PR programme.
2. To assess whether breathing and speech breathing patterns altered following a six week PR programme

3. To characterise breathing and speech breathing parameters and variability in pooled patients with CRD before, during and after six week PR programme.

Research question:

1. Do breathing and speech breathing patterns in pooled patients with CRD alter following a six week PR programme?

Hypotheses developed after data collection:

- HP6a** Modified Borg Scores significantly decrease following a six week PR programme.
- HP6b** Walking distance assessed during the ISWT significantly increases following a six week PR programme.
- HP6c** There is a statistically significant difference in mean **expiration time before** and after a six week PR programme in pooled patients with CRD during two minute periods of quiet breathing, reading, counting and conversational speech.
- HP6d** There is a statistically significant difference in **mean expiration magnitude** before and after a six week PR programme in pooled patients with CRD during two minute periods of quiet breathing, reading, counting and conversational speech.
- HP6e** There is a statistically significant difference in **mean respiratory rate** before and after a six week PR programme in pooled patients with CRD during two minute periods of quiet breathing, reading, counting and conversational speech.
- HP6f** There is a statistically significant difference in **mean %RCExp** before and after a six week PR programme in pooled patients with CRD during two minute periods of quiet breathing, reading, counting and conversational speech.

7.6.2 Clinical measures following Pulmonary Rehabilitation

COPD has been considered to be a heterogeneous condition with several localised and systemic manifestations (Lacasse et al. 2007; GOLD 2014), where a

range of standardised outcome measures have been traditionally examined before and after PR in order to determine the impact of the intervention (NICE 2010; BTS 2013). It was considered useful to examine physiological and symptomatic changes (exercise capacity and breathlessness) following PR, as it was thought that changes in these parameters might be associated with changes in breathing and speech breathing pattern. The following section will present the before and after changes in exercise capacity (measured during the ISWT) and self-reported breathlessness (measured using the Borg scale) following PR. These data were collected routinely by the clinicians running the PR programme and made available to the researcher via the medical notes.

7.6.3 Self-perceived breathlessness (Modified Borg Score)

Self-perceived breathlessness was rated on a 10-point Modified Borg scale (see Appendix 16) by each participant on the first and last day of PR (table 48). Both sets of data were examined for normal distribution using the Shapiro-Wilk tests and a decision was made to use non-parametric statistical tests, as the data were not normally distributed. Wilcoxon's Signed Rank Test for related samples was used to test for statistically significant differences between the breathlessness scores measured at before and after PR. The findings in table 48 are based on 17 patients because three patients did not complete the post PR breathlessness assessment. The reasons for this are unknown because the details were not documented by the respiratory physiotherapist.

	Mean \pm SD	Min max	p	Ranks		
				Positive	Negative	Tie
Before PR (n = 20)	1.43 \pm 1.21	0 - 3	0.76	4	5	8
After PR (n = 17)	1.47 \pm 1.41	0 - 4				

Negative ranks – Breathlessness after < breathlessness before; **Positive ranks** – Breathlessness after > breathlessness before; **Ties** – breathlessness after = breathlessness before

Table 48 Mean differences in self-reported breathlessness (Borg Score) and Wilcoxon's Signed Rank Test results; Pre and post PR in pooled patients with CRD

Following a six week PR programme, the majority of patients (tie; $n = 8$) maintained the same level of breathlessness as at baseline. Roughly the same number of patients had a lower breathlessness score after PR (negative ranks; $n=5$), than before PR (positive ranks $n = 4$) (table 48). Although the average Modified Borg Score for the group was slightly higher after the six week PR programme, the actual difference was exceptionally small (0.04) and was not statistically significant ($p = 0.76$). Furthermore, the average level of breathlessness reported by the group both before and after PR was very low in intensity (1 = “very mild shortness of breath”).

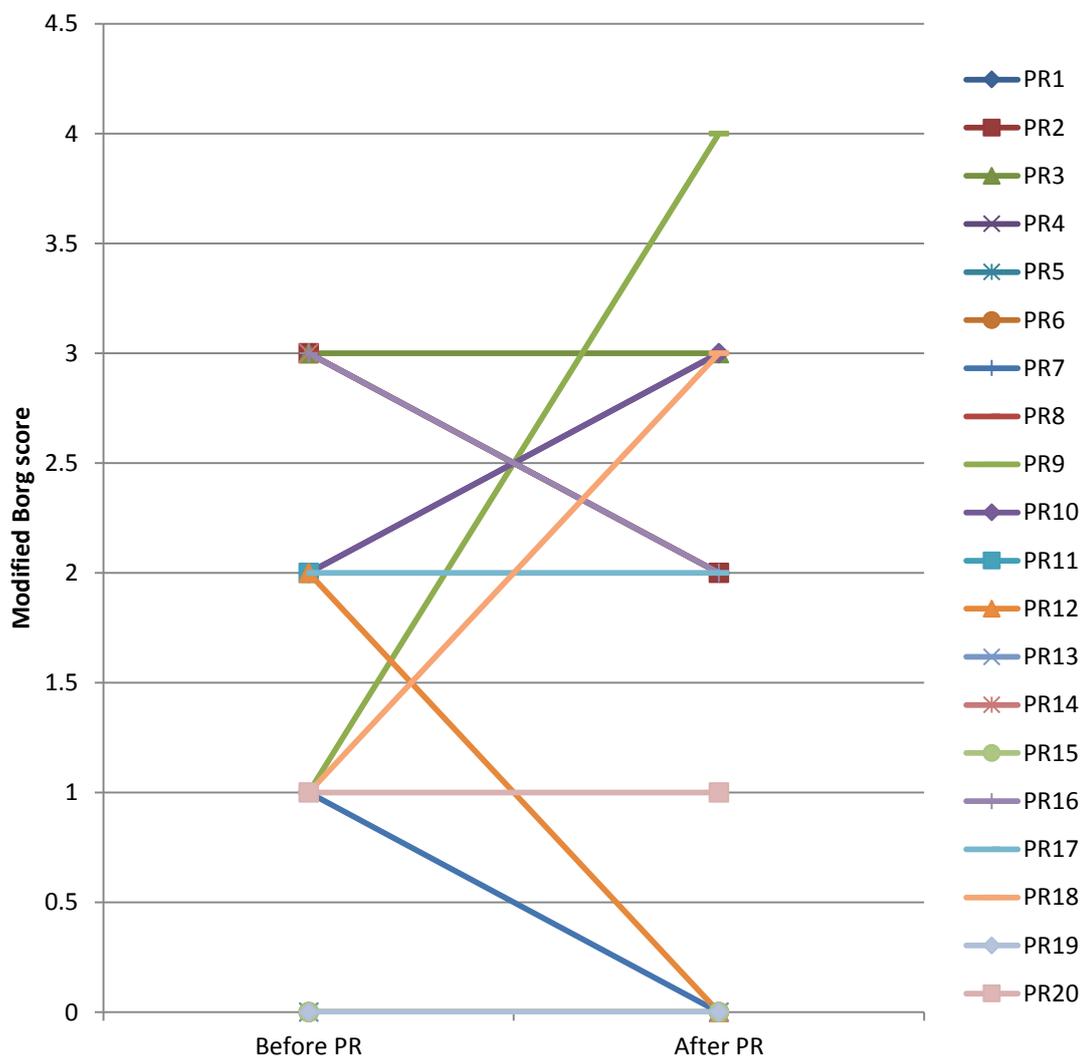


Figure 28 Individual before and after Modified Borg Scores in patients with COPD and bronchiectasis

Figure 28 presents the individual pre and post PR Modified Borg Scores for each member of the group. It can be seen that the majority of patients either maintain the same Borg score or decrease their score following PR. Four reported an increase in breathlessness following PR (PR1, PR9, PR10 and PR18). One individual increased from 1 to 4 (PR9), potentially skewing the average post measurement for the group. With this one exception, all of these scores remain within descriptors that range from ‘not at all’ to ‘moderate shortness of breath’.

7.6.4 Exercise capacity (ISWT)

Functional exercise capacity was measured by the clinical team via a ISWT on the first and last day of PR. Assessments of exercise capacity were based on the distance walked during the test, which was measured in metres. Both sets of data (pre and post PR) were checked for normal distribution, and a decision was made to use paired t tests, as the data were found to be normally distributed. Table 50 presents the mean walking distance (metres) for the group on the first and last day of a six week PR programme.

	Before PR	After PR	Mean diff (m)	95% CI of the mean difference		t	Df	p
				Lower;	Upper			
Mean walking distance (m) SD	166.47 (88.73)	255.29 (135.46)	88.82	-132.82	-44.82	-4.117	16	0.000*

*Significant at the 0.05 alpha level (2 tailed)

Table 50 Mean distance travelled during the ISWT before and after Pulmonary Rehabilitation in pooled patients with CRD (n=17)

Seventeen patients were included in the analysis comparing pre and post PR walking distance during the ISWT. Three patients did not participate in both tests (one missed the before test and two missed the after PR test), but the reasons for this were not documented by the physiotherapist. On average, the whole group increased their walking distance by 88.82m following a six week PR

programme. This finding was found to be statistically significant ($p = 0.000$) and exceeded the minimal clinically important difference (MCID) for the ISWT (47.5m) (Singh et al. 2008; Singh & al 2014). Figure 29 presents the individual walking distance scores (ISWT) pre and post PR.

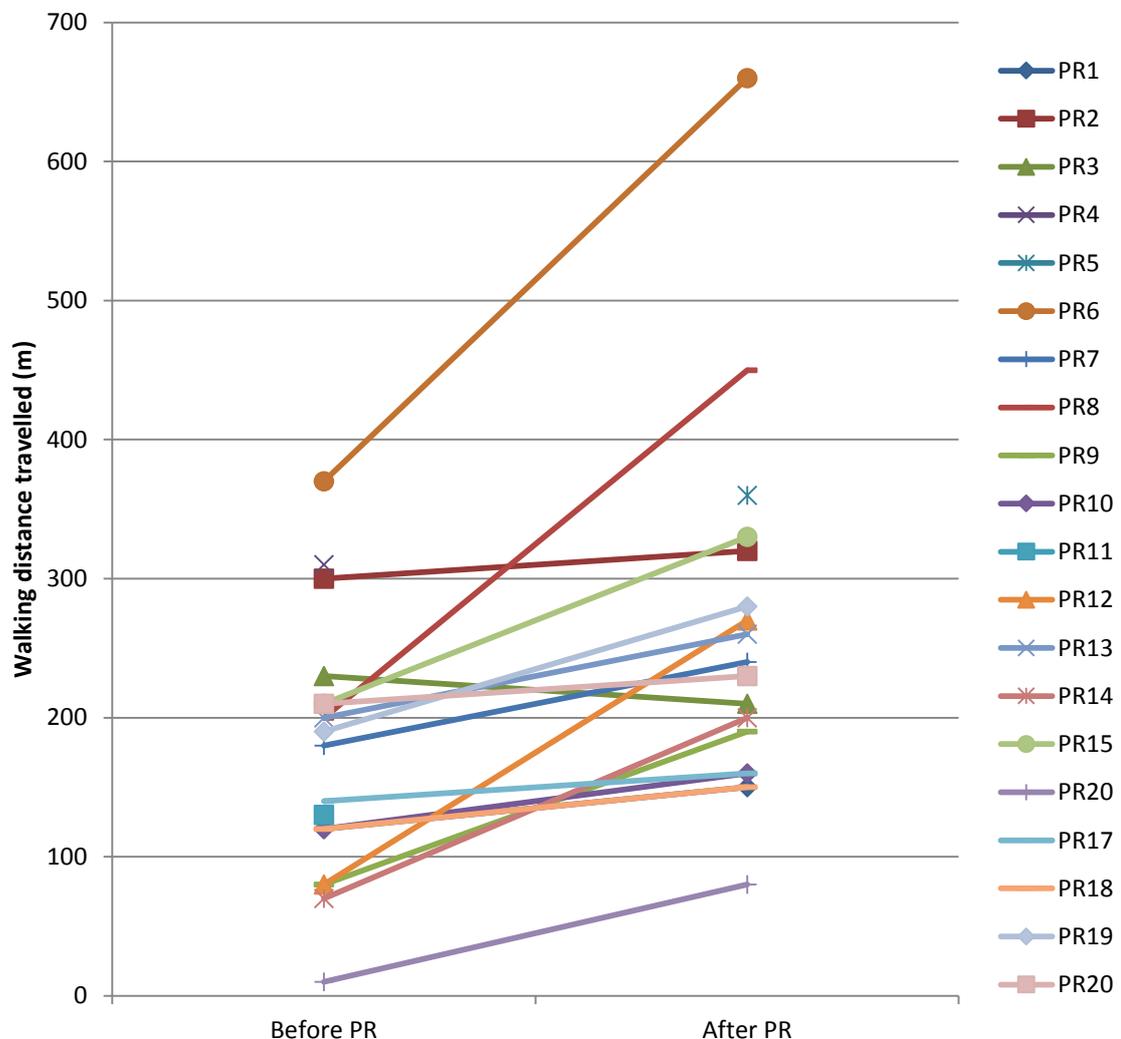


Figure 29 Individual distance (in metres) travelled by patients with COPD and bronchiectasis during the shuttle walk test at before and after the six week Pulmonary Rehabilitation programme n=17

Figure 29 presents the individual walking distances recorded during the ISWT at before and after PR. Only one patient (PR3) walked less far after PR, reducing from 230m to 210m. This difference is less than the MCID. All the other 16 patients increased their walking distance after the six week PR programme.

7.6.5 Modified Borg Score and physiological variables before and after ISWT; on the first and last day of PR

Heart rate (HR), saturation of oxygen (SpO₂) and Modified Borg Scores were also measured at four different time points by the clinical team: immediately before (1) and after (2) the ISWT, on the first day of PR, and immediately before (3) and after (4) the ISWT on the last day of PR. These variables were measured by the respiratory physiotherapist, and were extracted from patient medical notes by the researcher.

Since the Modified Borg Scores were in scale form and were not normally distributed, Wilcoxon's signed rank test for related samples was used to test for significant differences between the different time points. Differences in heart rate and oxygen saturation between the before and after ISWT and pre and post PR were assessed using paired t tests. These results are presented in table 51.

Based on the findings in table 51, the average modified Borg Scores were significantly higher after each ISWT than before each ISWT. They were also higher after PR than before PR, but the latter did not reach statistical significance. Heart rate was found to be significantly higher after the ISWT after PR. Oxygen saturation decreased after each shuttle walk test both before and after PR, however the difference between post shuttle walk tests before and after PR was not statistically significant.

	Before PR		After PR		Difference between pre and post shuttle before PR	Difference between pre and post shuttle after PR	Difference between post shuttle before PR and post shuttle after PR
	Pre Shuttle	Post shuttle	Pre shuttle	Post shuttle			
Borg Score Mean ±SD	1.43±1.21	3.50±1.68	1.47±1.41	4.31±1.58	+ 2.07*	+ 2.84*	+ 0.81
HR (bpm) Mean±SD	79.25±12.39	99.28±17.36	79.88±12.76	106.94±18.74	+ 20.03*	+ 28.41*	+ 7.25*
SpO₂ Mean±SD	94.75±2.02	91.79±4.54	95.00±1.96	91.61±5.12	-3.00*	- 3.70*	-0.17

*Starred results significant at the 0.05 alpha level

SD: Standard Deviation; HR: Heart Rate; bpm: beats per minute; SpO₂: Saturation of oxygen; PR: Pulmonary Rehabilitation

Table 51 Modified Borg score and physiological variables (HR and SpO₂) pre and post shuttle walk test, before and after a six week Pulmonary Rehabilitation in pooled patients CRD

7.6.6 Summary of clinical measures following PR

Resting Modified Borg Scores started low (1='very mild shortness of breath') and remained low after the six week PR programme, where the difference in the pre and post PR measurements was not found to be statistically significant. Apart from resting heart rate, which significantly increased post ISWT, post PR, the group physiological response to exercise was similar before and after PR. However, functional walking distance increased by an average of 88.82 metres for the group, which exceeded the MCID of 47.5m for the ISWT (Singh et al. 2008).

7.6.7 Breathing and speech breathing patterns before, during and after a six week Pulmonary Rehabilitation

Breathing and speech breathing parameters measured from 20 patients with COPD and bronchiectasis (pooled patients with CRD) have been analysed across three different time points; before, during (midway) and after a six week PR programme.

7.6.8 Missing data

Due to equipment failures that occurred during the third study, some data sets had to be removed from the analysis during each task at different time points. ANOVA requires complete data sets throughout all time points to conduct the analysis. For example, if data are missing from one participant at time point one, SPSS will remove the remaining data at time point two and three from the same participant. Consequently, the sample size during each task varied as follows: Quiet breathing (n = 13), Reading (n = 14), Conversation (n = 14), Counting (n = 13). Even though the removal of incomplete data sets meant that statistical power was reduced, it was considered inappropriate to impute the data because the original sample was too small to base any imputation on. A summary of all the missing data can be found in Appendix 19.

7.6.9 Breathing and speech breathing patterns before, during and after PR – results from the repeated measures ANOVA

Breathing and speech breathing pattern data that were obtained from the three different time points were tested for normality using the Shapiro Wilk test, and

found to be normally distributed. In order to examine mean differences in breathing and speech breathing parameters among time points, a one way repeated measures ANOVA was chosen to determine whether there were any statistically significant differences between the three time points. This is because there was one effect (time point), with three different levels (time points one, two and three). The Greenhouse Geisser correction was used when the assumptions of Mauchly's Test of Sphericity were violated. The results of the one way repeated measures ANOVA were unremarkable. No statistically significant differences were identified for any breathing parameter or task amongst any of the three time points. These results have been presented in Appendix 20.

As discussed, one of the limitations of employing a one way repeated measures ANOVA to assess the before, during and after differences in breathing and speech breathing pattern relates to the missing data in the current sample. This is because ANOVA in SPSS deals with missing data by automatically removing any incomplete data sets from the analysis. The majority of data losses occurred during the middle recording session were due to equipment failures. Removing missing data reduces the total number of participants included in each analysis, and ultimately reduces statistical power. It is possible that this contributed to the generation of Type two errors (false negatives).

Although data were collected at three time points, the main focus of interest was to look for any changes in breathing and speech breathing parameters from before to after a six week PR programme. Taking into account the missing data and the influence this has on the sample size, a decision was subsequently made to exclude the midpoint data and explore differences between time point one and three (before and after PR). The next section describes the results from this analysis.

7.6.10 Before and after differences in breathing and speech breathing parameters (between time point one and three) in patients with CRD

Examining the differences in breathing and speech breathing patterns exclusively between **time point one** and **three** (before and after PR) meant that data from more participants could be included in the sample for the quiet breathing, reading, conversation and counting task. Table 52 presents the difference in sample size between the ‘before, during and after analysis’, and the ‘before and after’ analysis

Task	Before, during and after PR analysis – sample size	Before and after PR analysis –sample size
Quiet breathing	13	14
Reading	14	18
Conversation	14	18
Counting	14	18

Table 52 Sample size used during the ‘before, during and after’ analysis in comparison to the ‘before and after’ analysis

7.6.11 Comparison between time point one and time point three

Respiratory rate, expiration time, expiration magnitude and %RCExp were compared between time point one and time point three. See section 7.5.2 for a justification for this choice of parameters. Paired t tests for related samples, adjusted via Bonferroni corrections were used to test for any significant differences, as the data were found to be normally distributed using the Shapiro-Wilk test (table 53-56).

Quiet breathing task

	Before PR (Time point 1) (n=14)	After PR (Time point 3) (n=14)	Mean difference	95%CI of the mean difference		<i>t</i>	<i>df</i>	<i>p</i>
				Upper;	Lower			
T_E (sec)	2.31±0.79	2.17±0.54	0.14	-0.21;0.49		0.86	13 ¹	1 ^{NB}
EM (a.u)	1.29±0.51	1.50±0.60	-0.20	-0.57;0.16		-1.21	13 ¹	0.96
RR (bpm)	16.78±4.54	17.11±3.94	-0.32	-2.48;1.83		-0.32	13 ¹	1 ^{NB}
%RC Exp	59.74±12.51	66.53±12.48	-6.79	-13.27;-0.30		-2.28	13 ¹	0.12

Bonferroni adjustment for multiple comparisons; ¹equal variances assumed

*Starred results significant at the 0.05 alpha level (2-tailed)

^{NB} *p* value capped at 1 one if *p* > 1 following Bonferroni corrections for multiple comparisons

RR=Respiratory Rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCExp = Percentage Ribcage contribution to expiration; DF = Degrees of Freedom;

Table 53 Before and after PR: Mean differences between breathing parameters measured at time point one and three during quiet breathing - Results of the paired sample t test

Reading task

	Before PR (Time point 1) (n=18)	After PR (Time point 3) (n=18)	Mean difference	95%CI of the mean difference		<i>t</i>	<i>df</i>	<i>p</i>
				Upper;	Lower			
T_E (sec)	3.22±0.71	3.12±0.62	0.10	-0.21;0.42		0.68	17 ¹	1 ^{NB}
EM (a.u)	1.33±0.38	1.40±0.62	-0.07	-0.42;0.28		-0.41	17 ¹	1 ^{NB}
RR (bpm)	16.00±2.91	16.40±3.04	-0.04	-1.91;1.11		-0.55	17 ¹	1 ^{NB}
%RC Exp	63.06±15.50	65.41±14.64	-2.34	-11.36;6.67		-0.54	17 ¹	1 ^{NB}

Bonferroni adjustment for multiple comparisons; ¹equal variances assumed

*Starred results significant at the 0.05 alpha level (2-tailed)

^{NB} *p* value capped at 1 one if *p* > 1 following Bonferroni corrections for multiple comparisons

RR=Respiratory Rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCExp = Percentage Ribcage contribution to expiration; DF = Degrees of Freedom

Table 54 Before and after PR: Mean differences between breathing parameters measured at time point one and three during the reading task - Results of the paired sample t test

Conversational speech task

	Before PR (Time point 1) (n=18)	After PR (Time point 3) (n=18)	Mean difference	95% CI of the mean difference		<i>t</i>	<i>df</i>	<i>p</i>
				Upper;	Lower			
T_E (sec)	3.74±1.09	3.86±1.25	-0.11	-0.58;0.34	-0.54	17 ¹	1 ^{NB}	
EM (a.u)	1.44±0.60	1.67±0.59	-0.23	-0.57;0.11	-1.40	17 ¹	0.72	
RR (bpm)	14.21±3.22	13.95±3.44	0.26	-0.76;1.28	0.53	17 ¹	1 ^{NB}	
%RC Exp	56.53±14.46	60.18±12.53	-3.64	-12.46;5.18	-0.88	17 ¹	1 ^{NB}	

Bonferroni adjustment for multiple comparisons; ¹equal variances assumed

*Starred results significant at the 0.05 alpha level (2-tailed)

^{NB} *p* value capped at 1 one if *p* > 1 following Bonferroni corrections for multiple comparisons

RR=Respiratory Rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCExp = Percentage Ribcage contribution to expiration; DF = Degrees of Freedom;

Table 55 Before and after PR: Mean differences between breathing parameters measured at time point one and three during the conversational speech task - Results of the paired sample t test

Counting task

	Before PR (Time point 1) (n=18)	After PR (Time point 3) (n=18)	Mean difference	95% CI of the mean difference		<i>t</i>	<i>df</i>	<i>p</i>
				Upper;	Lower			
T_E (sec)	3.55±1.82	3.66±1.47	-0.11	-0.77;0.54		-0.36	17 ¹	1 ^{NB}
EM (a.u)	1.21±0.52	1.30±0.73	-0.09	-0.50;0.31		-0.47	17 ¹	1 ^{NB}
RR (bpm)	16.37±5.54	15.91±5.70	0.46	-2.10;3.03		0.38	17 ¹	1 ^{NB}
%RC Exp	59.03±11.78	62.22±12.60	-3.19	-11.79;5.40		-0.78	17 ¹	1 ^{NB}

Bonferroni adjustment for multiple comparisons; ¹equal variances assumed

*Starred results significant at the 0.05 alpha level (2-tailed)

^{NB} *p* value capped at 1 one if *p* > 1 following Bonferroni corrections for multiple comparisons

RR=Respiratory Rate; T_E (sec) = expiration time (sec); EM (a.u) = Expiration magnitude (arbitrary units); %RCExp = Percentage Ribcage contribution to expiration; DF = Degrees of Freedom

Table 56 Before and after PR: Mean differences between breathing parameters measured at time point one and three during the counting task - Results of the paired sample t test

No statistically significant differences were found between the first and last PR session ($p > 0.05$) for any of the tasks or parameters examined. Individual data were then examined to determine whether there was any consistent direction of change during any of the tasks

7.6.12 Direction of change

The differences between the pre and post PR assessment were not found to be statistically significant for any of the breathing parameters or tasks. Since it was possible that the sample was inadequately powered to detect a significant difference, a decision was made to examine the data on a case-by-case basis to determine whether there was any consistent direction of change. These findings can be found in table 57, which presents the number of patients who were associated with an 'increase' or 'decrease' in the value of each breathing parameter.

Based on the findings in table 57, the direction of change was not found to be consistent for any of the breathing parameters and tasks. Therefore, these findings indicate that breathing and speech breathing patterns did not change in either a statistically or clinically significant manner.

7.6.13 Speech breathing variability before and after PR

The Co-efficient of Variation (CoV%) was used to examine the variability of breathing and speech breathing parameters at the two different time points (before and after PR). Table 58 presents the CoV% during each time point for the quiet breathing, reading, conversation and counting task. No consistent pattern was identified when examining the variability of each breathing parameter.

	Quiet breathing task (n=14)		Reading task (n=18)		Conversational speech task (n=18)		Counting task (n=18)	
	no. decreasing	no. increasing	no. decreasing	no. increasing	no. decreasing	no. increasing	no. decreasing	no. increasing
T_e (sec)	8	6	10	8	10	8	10	8
EM (a.u)	5	9	11	7	6	12	12	6
RR (bpm)	6	8	9	9	7	11	11	7
%RCInsp	5	9	9	9	10	8	9	9

T_e (sec) = expiration time (sec) EM (a.u) = Expiration magnitude (arbitrary); RR= Respiratory Rate; RC% Cont Exp = Ribcage percentage contribution to expiration

Table 57 Direction of change in breathing parameters from time point one to time point three in patients with CRD.

	<i>Quiet breathing task</i>		<i>Reading task</i>		<i>Conversational speech task</i>		<i>Counting task</i>	
	<i>Before PR (n=14)</i>	<i>After PR (n=14)</i>	<i>Before PR (n=19)</i>	<i>After PR (n=19)</i>	<i>Before PR (n=19)</i>	<i>After PR (n=19)</i>	<i>Before PR (n=19)</i>	<i>After PR (n=19)</i>
T_i (CoV%)	33.81±20.89	31.21±12.53	34.78±6.98	39.99±17.36	36.58±7.08	40.81±12.21	38.52±11.31	42.00±13.85
T_e (CoV%)	29.61±13.11	29.90±12.18	45.90±11.73	43.25±7.56	52.13±9.65	55.19±13.44	56.72±19.11	56.57±15.56
IM (CoV%)	33.03±15.60	33.61±14.47	38.15±9.54	41.47±8.08	42.02±10.75	43.71±10.81	40.82±12.62	45.40±14.82
EM (CoV%)	32.40±13.96	33.23±14.36	45.90±11.73	44.14±9.10	47.45±10.41	52.60±15.29	49.14±13.76	54.22±16.14
T_{tot} (CoV%)	23.07±11.06	23.67±9.61	39.40±11.03	37.28±6.92	45.00±7.30	46.64±11.13	48.25±14.85	49.09±16.66
RR (bpm)	28.42±4.94	23.02±3.94	15.37±2.95	18.15±3.00	22.66±3.27	25.12±3.58	32.89±5.45	34.71±5.54
%RCInsp (CoV%)	15.31±13.12	12.17±9.27	14.54±7.38	17.44±11.86	16.35±12.66	27.69±25.04	16.31±10.18	20.85±14.40
%ABInsp (CoV%)	20.25±13.62	28.69±21.63	21.24±19.60	29.84±18.19	25.17±19.02	31.92±18.05	24.03±10.90	43.44±31.38
%RCExp (CoV%)	18.82±19.27	13.10±11.01	23.11±20.65	26.72±19.73	24.45±11.84	48.91±18.55	18.16±24.99	21.74±15.46
%ABExp (CoV%)	20.54±15.62	21.23±17.49	33.20±19.41	39.13±27.96	42.61±25.65	38.88±19.45	30.68±12.63	33.86±18.76

CoV% = Coefficient of Variation expressed as a percentage; T_i(sec) = Inspiration time (seconds); T_e (sec) = expiration time (sec); IM (a.u) = inspiration magnitude (arbitrary units); EM (a.u) = Expiration magnitude (arbitrary units); T_{tot} (sec) = breathing cycle time (sec); RR (bpm) = respiratory rate (breaths per minute); %RCInsp = Ribcage percentage contribution to inspiration; %ABInsp = Abdominal percentage contribution to inspiration; %RCExp = Ribcage percentage contribution to expiration; %ABExp = Abdominal percentage contribution to expiration

Table 58 Co-efficient of Variation (expressed as a percentage) during the quiet breathing, reading, conversation and counting task: Before and after PR

7.6.14 Summary of section six

The following table presents a summary of findings with respect to the hypotheses described in section 7.6.1. A complete summary of chapter five will then be given in section 7.7.

Table 60 Summary of section six

Hypotheses	Summary of findings	Rejected/partially supported/supported?
HP6a	<ul style="list-style-type: none"> The difference in Modified Borg Scores was not statistically significant between the first and last day of PR. 	Rejected
HP6b	<ul style="list-style-type: none"> The difference in mean walking distance (measured during the ISWT) increased by 88.82m which was found to be statistically significant ($t=4.11$, $df=16$, $p=0.00$). 	Supported
HP6c	<ul style="list-style-type: none"> The difference between time point one and time point three was not statistically significant for expiratory time ($p>0.05$) during any of the breathing or speech tasks. 	Rejected
HP6d	<ul style="list-style-type: none"> The difference between time point one and time point three was not statistically significant for expiratory magnitude ($p>0.05$) during any of the breathing and speech tasks. 	Rejected
HP6e	<ul style="list-style-type: none"> The difference between time point one and time point three was not statistically significant for respiratory rate ($p>0.05$) during any of the breathing and speech tasks. 	Rejected
HP6f	<ul style="list-style-type: none"> The difference between time point one and time point three was not statistically significant for %RCExp ($p>0.05$) during any of the breathing and speech tasks. 	Rejected

7.7 Summary of the results chapter

In this chapter, the data from the three studies conducted during this research have been analysed and presented.

The main findings from this body of research are as follows:

1. Breathing/speech breathing parameters relating to respiratory timings and regional contributions of the chest wall were able to significantly differentiate between healthy older adults and pooled patients with CRD during every breathing and speech task.
2. The conversational speech task was found to produce the greatest number of significant differences between healthy older adults and pooled patients with CRD
3. The describing task used in the first study was found to be an ineffective surrogate for spontaneous speech because of difficulties encountered with describing the images.
4. There was no evidence that pooled patients with CRD produced task specific breathing patterns. Although inspiratory and expiratory times were found to significantly differentiate between quiet breathing and speech, no statistically significant differences were detected between any of the speech tasks.
5. In contrast, breathing patterns were found to be task specific in healthy younger adults, as statistically significant differences were observed between constrained (reading) and unconstrained speech (conversational speech) for all respiratory timings and magnitudes.
6. This distinction became less clear in healthy older adults. Only five breathing parameters were able to significantly differentiate between the breathing and speech tasks.
7. Breathing and speech breathing parameters could not significantly differentiate between patients with COPD and bronchiectasis.
8. Breathing/speech breathing patterns in pooled patients with CRD did not alter following a six week PR programme. The differences between the first and last PR session were not found to be statistically significant for any breathing parameter or task.

9. Functional walking distance increased significantly (both clinically and statistically) after a six week PR programme. However, no such changes in breathlessness were detected.
10. A recording period of two minutes was sufficient to provide stable breathing parameters in healthy younger adults.
11. A linguistically 'constrained' task (reading) was associated with the shortest respiratory timing components, smallest breath sizes and fastest respiratory rates in healthy and patient groups of all ages,
12. A 'linguistically unconstrained' task (conversation) was associated with the longest respiratory timing components, largest respiratory magnitudes and slowest respiratory rate in healthy and patient groups of all ages.
13. Multiple linear regression suggested age might influence the regional contributions of the ribcage and abdomen during quiet breathing and speech in healthy adults.
14. Multiple linear regression suggested that sex had no significant influence on breathing and speech breathing patterns in healthy adults.
15. Comparisons between healthy young adults and adults with self-reported asthma showed that there might be significant differences between the two groups during a quiet breathing task, but not during speech.

In the next chapter, these findings will be discussed in relation to the existing literature in the field, and the methodological limitations will be identified from the three studies. Recommendations for future research will then be presented.

Chapter Eight

Discussion

Introduction

There is a small body of literature associated with speech breathing patterns, of which the majority has involved small samples (less than $n=15$) of healthy adults. Most of this work originates from the 1970's and 1980's using technology that is now dated. In the early studies, speech signals were obtained from audiotapes, and breathing cycles were identified from the RIP signal using aural detection of the speech signals, which were played through audiotapes (Hoit & Hixon 1986; Hoit & Hixon 1987; Hodge & Rochet 1989; Hoit et al. 1989; Winkworth et al. 1994). This practice introduced an element of subjectivity to their measurement, as the detection of speech relied on the hearing ability of the observer. There are no published speech breathing data from patients that have been quantified using modern signal analysis techniques. A range of different speech tasks have been used in the past to assess speech breathing patterns, such as reading, describing, conversational speech and counting (Loudon et al. 1988; Hodge & Rochet 1989; Solomon & Hixon 1993). However, the type of speech that provides the most useful information about lung health is currently unknown, as speech breathing pattern analysis has yet to be evaluated for its potential to be used as a respiratory monitoring tool.

The main aims of this body of research were: to evaluate protocols for speech breathing pattern research, to explore the characteristics and specificity of breathing and speech breathing patterns in healthy adults and patients with chronic respiratory diseases, and to evaluate the potential of speech breathing patterns to be used as a monitor of respiratory health. The latter was examined by a) comparing speech breathing patterns between healthy adults and patients' chronic respiratory disease, and b) comparing breathing and speech breathing patterns before and after a clinical intervention (PR) of known effect.

The discussion has been organised under nine headings:

1. Evaluation of the speech tasks and the stability of speech breathing patterns over short periods of time
2. Characterisation of breathing and speech breathing patterns;
 - a. In healthy younger adults
 - b. In healthy older adults
 - c. In patients with chronic respiratory disease (self-reported asthma, COPD, bronchiectasis and in pooled patients with CRD).
3. Task specificity of breathing and speech breathing patterns
 - a. In healthy younger adults
 - b. In healthy older adults
 - c. In patients with chronic respiratory disease (self-reported asthma, COPD, bronchiectasis and in pooled patients with CRD).
4. The variability of breathing and speech breathing patterns
 - a. In healthy younger and older adults
 - b. In pooled patients with CRD
5. The influence of age and sex on breathing and speech breathing patterns in healthy adults
6. The influence of chronic respiratory disease on breathing and speech breathing patterns
7. The responsiveness of breathing and speech breathing patterns to a clinical intervention (PR) for patients with COPD or bronchiectasis
8. Limitations and technical issues
9. Summary

8.1 Evaluation of the speech tasks used in this research and the stability of speech breathing patterns over short periods of time

If speech breathing pattern analysis is to be considered as a respiratory monitoring tool in future clinical practice, the optimal protocols that provide the most useful speech breathing data firstly need to be established.

8.1.1 Evaluation of the speech tasks

Previous authors have used various reading, counting, describing and conversational tasks to assess speech breathing patterns (Loudon et al. 1988; Hoit et al. 1989; Sperry & Klich 1992; Winkworth et al. 1995). A describing task was included during the first study in this research. However, it was observed that participants frequently had to pause and think about their upcoming sentence when interpreting the pictorial material, possibly because the describing task was influenced by cognitive demand (Mitchell et al. 1996). Unlike the reading task, where speech was dictated by the pre-scripted text, or the conversational task, where individuals could easily describe their daily events, the describing task seemed to be more challenging for participants to complete fluently.

The reading task was selected for its 'easy' reading level based on the Flesch readability score (88). It was speculated that the easy reading level would encourage participants to read fluently, even when in a pressured environment, when participants were aware that their speech was being recorded during the task. The describing task was chosen as a surrogate for spontaneous speech. Participants were asked to look at pictures and describe the material based on their interpretation of what they saw. Such interpretation may influence speech breathing patterns because it requires an element of higher cognitive functioning. The prolonged inspiratory time that was seen may have occurred because participants had to think about their upcoming sentence, perhaps because they were unfamiliar with the material they were asked to describe. The influence of cognitive demand on speech breathing patterns has been previously investigated by Mitchell *et al* (1996) who used respiratory magnetometers to record breathing patterns from 20 healthy adults during two reading tasks that differed in their cognitive-linguistic planning requirements. Although data obtained by magnetometers may not be directly comparable to data obtained from the RIP because of differences in the way that changes in the cross sectional area of the rib cage and abdomen are quantified (see chapter 2.3.6), Mitchell *et al* (1996) found that cognitively demanding speech tasks were associated with a significant increase in the number of pauses, and average inspiratory time was significantly longer. Fewer syllables were produced per breathing cycle and speaking rate was slower during the higher cognitive load speech tasks, but these elements were not examined in this research because

linguistic parameters were not of primary interest. These findings suggest that cognitively demanding tasks influenced fluency related measures. Participants took 'inappropriate' breaths (or pauses), which were not in response to metabolic demand or at grammatically appropriate locations (during reading).

Due to the challenges experienced during the describing task in the current research and the possible influence of cognitive demand that has been previously reported (Mitchell et al. 1996), a decision was subsequently made to remove the describing task from the second and third studies, and replace it with a counting task. A counting task has previously been shown to highlight significant differences between healthy adults and patients with asthma. The task was reported to cue priority to communication, which could not be sustained by patients who were respiratorily compromised (Loudon et al. 1988).

It is acknowledged that the difficulties encountered during the describing task used in the first study may have been associated with the nature of the complex images, and that the selection of a more 'accessible' image may have solved this issue. With hindsight, the nature of the images used during the describing task may have been too complex for participants to describe fluently, especially within a pressured environment where participants were fitted with the RIP bands and a head-set microphone. Therefore, the selection of a more accessible image may have encouraged participants to describe the images more fluently, without needing to pause and think about their up-coming sentences. The principle reason for not swapping to an alternative image was because it was speculated that participants would have less visual material to describe, and thus fewer items to discuss. The use of simpler images could mean participants would run out of things to say before the recording period ended. Furthermore, the describing task was originally chosen as a surrogate for spontaneous speech. The conversational speech task was familiar to the participants and was consistently performed well by all participants, as they were able to speak fluently in the absence of pausing and thinking about their upcoming sentence.

8.1.2 The stability of breathing/speech breathing patterns over time in healthy adults

Although a little is known about speech breathing patterns recorded on a single occasion, the stability of speech breathing patterns over short periods of time has not previously been investigated. Therefore, no previous data is available for

comparison. Because speech introduces a 'linguistically random' component in to the breathing pattern (Brack et al. 2002) , the variability of speech breathing parameters is higher than quiet breathing (Winkworth et al. 1994). However, currently it is not known if these variations remain stable over different time periods. This information is needed to determine the minimum period of recorded speech from which one may extract useful data on speech breathing patterns. Previous variability studies have used a range of recording durations, ranging from the analysis of only 25 breathing cycles (Loudon et al. 1988), to longer periods of up to eight minutes (Mitchell et al. 1996). The findings from the within-recordings stability analysis indicated that speech breathing patterns remained stable when examined over each minute, for a period of four minutes, during quiet breathing, conversation, describing and reading. Visual inspection of the data suggested minimal fluctuation between time periods and no statistically significant differences were found for any breathing parameter or task. These findings supported the decision to reduce the period of time that was used to record speech breathing patterns. Reducing the recording time would improve the efficiency of speech breathing protocols, and be of particular benefit in patients with chronic respiratory disease who experience speaking related breathlessness.

8.1.2 Summary

This research suggests that in terms of speaking task selection, describing is not the optimal task for use during speech breathing assessments. In terms of optimal recording time, no statistically or clinically significant differences were identified for any parameter of task amongst the various time periods, thereby giving support to the use of shorter recording periods (two minutes) during speech breathing assessments.

8.2 Breathing and speech breathing characteristics

The characteristics of breathing and speech breathing patterns in relation to the existing literature will now be discussed according to 1) healthy younger adults 2) healthy older adults and 3) chronic respiratory disease (self-reported asthma, COPD, bronchiectasis and pooled patients with CRD). Since speech breathing

characteristics will be discussed at various points throughout this chapter, a discussion of the main findings will be presented in attempt to avoid repetition.

8.2.1 Breathing and speech breathing characteristics in healthy younger adults

In agreement with previous authors, quiet breathing and speech breathing patterns were different from each other (Tobin et al. 1983a; Hodge & Rochet 1989; Winkworth et al. 1994). While **quiet breathing** patterns were characterised by having similar inspiration and expiration timings, **speech breathing** patterns were characterised by having a short inspiratory phase, followed by a prolonged expiration. Adapting the proportions of the breathing cycle to form what has been described as the 'saw tooth' pattern provides the optimal conditions for speech (Hodge & Rochet 1989; Lee et al. 1993). Shortening inspiratory time during speech allows silences to be reduced, while a prolonged expiration phase extends the time available for speech production (Winkworth et al. 1995; Hoit & Lohmeier 2000). These differences were also reflected by the percentage of time spent on inspiration ($T_i/T_{tot}\%$), which during the speech tasks was roughly half the percentage of inspiratory time during the quiet breathing task.

Previous studies have reported similar findings during periods of resting breathing in healthy young adults (Tobin et al. 1983a). In a similar observational study, 47 young adults (mean age=28.6±5.3 years) underwent resting breathing pattern recordings using RIP (Tobin et al. 1983a). Although recordings were obtained in the supine position, and the recording period used for data extraction was not defined, similar findings relating to respiratory timing components were documented during resting breathing, as inspiration time and the proportion of time spent on inspiration ($T_i/T_{tot}\%$) was reported to be 1.60±0.30 seconds and 42% respectively. Respiratory rate appeared to be slower in the current research (14.11±3.85 bpm compared to 16.7±2.7 bpm in the study by Tobin *et al* (1983)). However, both values remained within the accepted normal range (Hough 2001).

Task related differences were observed between the linguistically constrained (reading) and the linguistically unconstrained speech tasks (conversational speech and describing). Task specific differences will be evaluated in detail in

section 8.3. However, in brief, the linguistically constrained task was found to have the shortest respiratory timing components, fastest respiratory rate and the smallest magnitudes. In contrast, the linguistically unconstrained tasks had the longest respiratory timing components, largest magnitudes and slowest respiratory rate.

In a previous observational study using RIP, Lee *et al* (1993) documented the timing elements of speech breathing patterns in 16 healthy adults (mean age=39.8±14.0 years) during a conversational speech task. Their study reported similar values for inspiration time (0.68±0.50 seconds). However, the proportion of time spent on inspiration was longer (19% in comparison to 15% in the current research), and their expiration time was shorter (3.64±2.08 seconds in comparison to 4.24±1.08 seconds). Respiratory rate and breathing cycle time were not documented. The large standard deviations reported in the study by Lee *et al* (1993) suggest that greater variability may have existed in their data set. The reasons for the different findings could be due to differences between characteristics and methodologies. For example, participants in the study by Lee *et al* (1993) were older, lying at a 15 degree angle from vertical towards supine, and the analysis was based on only 50 breaths which were subjectively selected for analysis. The differences between these findings indicate the sensitivity of speech breathing patterns to the measurement procedure. Furthermore, these findings highlight the challenges associated with interpreting the components of breathing/speech breathing patterns because of the absence of rigidly defined normative values for respiratory timing parameters.

8.2.2 Breathing and breathing and speech breathing characteristics in healthy older adults

As discussed, the bulk of knowledge regarding speech breathing patterns in healthy adults has been documented in studies involving young adults (Hoit *et al.* 1990; Sperry & Klich 1992; Manifold & Murdoch 1993). Speech breathing studies involving healthy older adults have primarily examined breathing parameters relating to subdivisions of lung volume and syllable production (Hoit & Hixon 1987). Few data are available in relation to respiratory timing components, relative volumes and regional contributions of the ribcage and abdomen in healthy older adults. Since the speech breathing pattern data in healthy older adults will be contrasted between the tasks, and with data from

healthy younger adults, this section will briefly discuss the characteristics of speech breathing patterns in healthy older adults in attempt to avoid repetition.

During quiet breathing, breathing patterns in healthy older adults were characterised by having a slightly longer expiration (2.82 ± 0.81 seconds) than inspiration phases (1.74 ± 0.50 seconds), similar inspiratory and expiratory magnitudes (1.69 ± 0.64 a.u. *versus* 1.68 ± 0.61 a.u), and a respiratory rate which remained within normal limits (14.04 ± 3.54 bpm). A previous observational study using RIP reported similar findings to the current investigation, as inspiratory time and respiratory rate were reported to be 1.67 ± 0.30 seconds and 16.6 ± 2.8 bpm respectively in 19 healthy older adults (mean age = 68.9 ± 6.5) (Tobin et al. 1983a). On visual inspection, healthy older adults also appeared to adapt their breathing pattern in response to speech, producing shorter inspirations and longer expirations during conversational speech, reading and counting.

One of the major age related changes in respiratory mechanics is chest wall compliance (Lanteri & Sly 1993; Huber & Spruill 2008). Chest wall movements during inspiration and expiration were dominated by the ribcage contribution during quiet breathing and speech tasks, with little mean differences between the tasks. The ribcage contribution in healthy older adults accounted for between 82 and 84% of the overall contribution to tidal breathing. In a previous study, Hoit *et al* (1989) measured speech breathing patterns using magnetometers in 30 healthy females representing three age groups (25, 50 and 75 years) during a spontaneous speech task. Their results showed that the relative volume contribution of the ribcage increased with age (25 years = 69.71 ± 11.86 , 50 years = 79.38 years and 75 years = 89.39 ± 7.61 years), although the differences between the age groups were non-significant ($F=1.25$, $df=29$, $p=0.30$). A greater ribcage contribution is needed to provide sufficient respiratory elastic recoil pressures, which naturally reduce with age (Janssens et al. 1999). The ribcage contribution in the older group (75 years) in the study by Hoit *et al* (1989) was greater than the ribcage contribution to inspiration and expiration observed in the current study, possibly because their participants were older in age, and the different methods used to measure speech breathing patterns. Hoit *et al* (1989) measured speech breathing patterns using magnetometers. As discussed, one of the limitations regarding this measurement system is that the cross sectional changes of the ribcage and

abdomen is concentrated on the anterior surface of the chest. Magnetometers do not measure the movement induced from the transverse displacements of the chest, which might provide a less accurate reflection of breathing pattern than RIP. Furthermore, Hoit *et al* (1968) did not define the period used to measure speech breathing patterns, and analysis was based on ten breathing cycles that were obtained from the start of the recording period. Selecting breathing cycles from the beginning of a recording could mean selecting cycles more likely to be influenced by anxiety, because participants are within an unusual environment. These results further demonstrate the challenges faced with interpretation of speech breathing patterns from specific subgroups, because of the lack of comparable published data obtained using standardised protocols.

8.2.3 Breathing and speech breathing characteristics in patients with chronic respiratory disease (COPD, bronchiectasis and adults with self-reported asthma)

Patients with COPD

Research examining speech breathing patterns in patients with chronic respiratory disease has been limited. In the current research, patients with COPD demonstrated adaptations in their respiratory cycle in response to speech. During quiet breathing, patients with COPD (n=10) had mean inspiration timings of 1.59 ± 0.71 seconds and mean expiration timings of 2.36 ± 0.86 seconds, where resting respiratory rate was 16.90 ± 5.41 bpm. A previous observational study which employed RIP to record resting breathing patterns in 12 patients with COPD found that respiratory timing components were shorter and respiratory rate was faster than in the current study (inspiratory phase 1.10 ± 0.20 seconds, respiratory rate 23.3 ± 3.3 bpm) (Tobin *et al.* 1983b). According to standard text book reference values, the respiratory rate documented in the study by Tobin *et al* (1983b) exceeded the normal range of 12 to 18 bpm (Hough 2001). One possible explanation for the differences between these findings could be because their patients had greater airway obstruction. This was indicated by their FEV_{1pp}, which was $32 \pm 6\%$ in comparison to $46 \pm 14\%$ in the in the current research. More severe airway limitation could have a negative impact on breathing parameters, especially respiratory rate because of the increased respiratory drive (Aliverti & Macklem 2001).

To date, only one study has characterised speech breathing patterns in patients with COPD during a conversational speech and counting task. Using RIP, Lee *et al* (1993) extracted respiratory timing parameters from 15 patients with emphysema (now defined as COPD). On average, inspiratory and expiratory time were reported to be 0.64 ± 0.27 and 2.51 ± 1.31 seconds respectively; both components were shorter than those observed in this research ($n=13$) (inspiration time= 0.74 ± 0.17 seconds and expiration time= 3.73 ± 1.23 seconds). The shorter respiratory timing components in the study by Lee *et al* (1993) suggest that respiratory rate may have been faster than that observed in this research, however this parameter was not extracted in their study. One explanation for these differences could be that the study by Lee *et al* (1993) recorded speech breathing patterns throughout a five minute period, while speech breathing patterns were recorded during a two minute period in this research. Increasing the length of the speech recordings might have placed a greater ventilatory demand on the patients in the study by Lee *et al* (1993), because the competition between speech and gas exchange would have been more pronounced over a longer time period. Methodological differences such as the nature of the conversational speech task may have also accounted for the differences, although description of the conversational speech task was not provided by Lee *et al* (1993). While no studies have previously examined speech breathing patterns in patients with COPD during a reading task, the findings obtained during the a counting task were very similar to what has previously been documented, as inspiratory and expiratory time were reported by Lee *et al* (1993) to be 0.58 ± 0.3 and 3.64 ± 2.34 seconds respectively, in comparison to 0.64 ± 0.24 seconds and 3.48 ± 1.79 seconds in this research.

Patients with bronchiectasis

No published data on speech breathing patterns in patients with bronchiectasis are available for comparison. On visual inspection, patients with bronchiectasis also maintained a saw tooth breathing pattern during speech, where respiratory timing components were shorter than patients with COPD in the current research. Since no existing data are available for comparison, speech breathing characteristics will be evaluated in more detail in section 8.6, where there findings have been contrasted with speech breathing data obtained from patients with COPD.

Adults with self-reported asthma

The research examining speech breathing patterns in patients with asthma has also been limited. In the current research, adults with self-reported asthma had the shortest inspiratory time of all groups (0.49 ± 0.08 seconds), while their expiration phase was roughly seven times longer (3.84 ± 0.76 seconds) during a two minute conversational speech task. From the limited comparable data available, the patients with asthma in the study by Louden *et al* (1983) had a longer inspiration time (0.79 ± 0.37 seconds), and therefore spent a greater proportion of the respiratory cycle on inspiration ($T_i/T_{tot}\% = 27\%$), when compared to the findings from the current research ($T_i/T_{tot} = 11\%$). Louden *et al* (1983) concluded that the longer inspiratory time observed in patients with asthma was directly attributed to the airways obstruction, causing them to prioritise gas exchanges (during speech). As a consequence, the time available for speech was reduced. Although methodological differences may have accounted for the differences in observed $T_i/T_{tot}\%$, one of the major reasons for these differences could be attributed to the differences in the severity of asthma. In the current investigation, asthma status was self-reported but in the study by Louden *et al* (1983) patients were clinically diagnosed. It is therefore not known if the asthma group in this investigation had a diagnosis of asthma, or what their severity was. Due to these uncertainties, adults who reported a history of asthma were excluded from the pooled analysis in section 7.5.7.

Summary of section 8.2

The characteristics of breathing and speech breathing patterns have been reviewed across a group of healthy adults (young and old) and patients with chronic respiratory disease (COPD, bronchiectasis and adults with self-reported asthma). As has been previously documented, all participants were shown to adapt their breathing cycles in response to speech production. The difference between published data and the findings herein in terms of the specific quantification of elements of breathing pattern parameters during speech may be due to methodological differences. These findings highlight the lack of well-defined normative speech breathing reference values obtained using standardised protocols, which will be needed if speech breathing pattern analysis is to become considered in clinical practice.

8.3 Task specificity of breathing and speech breathing patterns

8.3.1 Task specificity in healthy younger adults

Previous published research has suggested that speech breathing patterns are task specific in healthy adults. The findings from the analysis of the healthy younger adult data support this view.

Timing and relative volume parameters

The findings from the repeated measures ANOVA demonstrated that all breathing parameters showed some significant differences across the group of breathing and speech tasks. However, only expiratory timing was consistently different between every task comparison. Physiologically, since speech is spoken in the expiratory phase of the breathing cycle, the duration of the expiratory phase is determined by the nature of speech (Hoit et al. 1989; Winkworth et al. 1995). These findings suggest that expiratory timing may be more sensitive to the type of speech, in comparison to the other breathing parameters.

Speech breathing behaviours were noticeably different during the linguistically ‘constrained’ speech task (reading) and the linguistically unconstrained tasks (describing and conversation). In particular, the reading task was associated with the shortest respiratory timing components and smallest breath volumes, compared to describing and conversational speech task. As a consequence, the fastest respiratory rates were observed during the reading task. None of the participants in this healthy sample reported any previous or current respiratory disease. All participants were able to maintain this pattern of breathing during speech without becoming respiratorily compromised, since the average respiratory rate remained within a ‘normal’ range (Hough 2001), even during the reading task.

These findings demonstrate the influence of ‘constrained speech’ (that is, the grammatical constraint of pre-scripted dialogue) on ventilation. In theory, breaths are usually taken at ‘grammatically appropriate’ locations, for example at sentence boundaries, full stops and new paragraphs (Grosjean & Collins 1979). The pre-scripted structure of the reading task meant that participants were cued to pause (and breathe) in response to these locations. During the

reading task, participants did not have as much freedom to vary their sentences and to breathe in response to ventilatory demands. The findings suggest that the reading task was more respiratorily demanding than the spontaneous speech task, because the reading task was associated with the fastest respiratory rate. However, despite an increase from quiet breathing, respiratory rate remained within normal limits during the reading task in healthy young adults, which supports the theory that healthy adults are able to maintain the competition between speech and ventilatory requirements, without becoming respiratorily compromised (Bunn & Mead 1971; Loudon et al. 1988; Lee et al. 1993).

Regional contributions of the rib cage and abdomen

The recognition of 'task specific' breathing patterns during different types of speech is not a new finding (Hoit et al. 1989; Sperry & Klich 1992; Winkworth et al. 1995). However, these early observations were based only on the evaluation of respiratory timing and volume parameters. In this research the regional contributions of the rib cage and abdomen in relation to speech task specificity in healthy young adults have been studied for the first time. The analysis revealed task specific differences for each parameter, except for the abdominal contribution to inspiration ($F=2.14$, $df=3$, $p=0.09$). However, while results from the repeated measures ANOVA identified %RCInsp, %RCExp and %ABExp as statistically significant, post hoc tests revealed that the differences were significant between the quiet breathing and the describing task, but not between any of the speech tasks. These findings suggest that the displacements of the chest wall remain fairly stable between speech tasks. On average, the ribcage contribution was found to be greater (and hence the abdominal contribution smaller) during the quiet breathing task in comparison to the speech tasks. A greater abdominal contribution may be necessary during speech tasks to generate intra-abdominal pressure to maintain a prolonged expiratory phase (Hixon et al. 1973; Hixon et al. 1976). This finding is in agreement with earlier observations, that abdominal muscle activity is more pronounced during speech activities (Hixon et al. 1973).

8.3.2 Speech task specificity in healthy older adults

Timing and volume parameters

Unlike healthy younger adults, the distinction between the speech tasks became less profound in healthy older adults. The majority of speech breathing research documenting 'task specific' breathing patterns is based on data from young adults (Hodge & Rochet 1989; Winkworth et al. 1994; Winkworth et al. 1995), so there is limited existing research available for comparison. The linguistically constrained tasks (counting and reading) were associated with the shortest inspiratory and expiratory phases, smallest respiratory magnitudes, shortest breathing cycles and fastest respiratory rates. However, while the analysis (ANOVA) of healthy younger adults revealed that all respiratory timings and magnitudes were statistically significant, only four of the breathing parameters were identified by the ANOVA as being statistically significant. To date, no other studies have exclusively examined task specific breathing parameters in healthy older adults. Hoit *et al* (1987) examined the influence of age on speech breathing patterns, although they did not compare any parameters between the tasks. This finding from the current research suggests that 'task specific' breathing patterns are less likely to be found in older populations. While the small sample size may have been insufficiently powered to detect a significant change, the findings from the healthy younger adults were also based on similar sample size (n=29).

Physiological factors associated with age could also account for the distinction between the speech tasks being less clear in healthy older adults. Increasing age has been shown to be negatively associated with lung compliance (due to the progressive loss in elastic recoil) and inspiratory muscle strength (Mittman et al. 1965; Lanteri & Sly 1993; Lalley 2013). These anatomical adaptations to age result in greater difficulty in generating adequate subglottic pressures to sustain the production of speech, and have been thought to affect intelligibility and audibility of speech (Binazzi et al. 2006). Due to these anatomical adaptations, healthy older adults have been reported to initiate speech at higher lung volumes, and produce fewer syllables per breath compared to younger individuals, as a compensatory mechanism (Hoit & Hixon 1987). Therefore, the observation that the ability to produce task specific breathing patterns decreases in healthy older adults could stem from the challenges associated

with generating adequate subglottic pressures with increasing age, reducing ability to modify speech.

Regional contributions of the ribcage and abdomen

The findings in relation to ribcage and abdominal contributions in healthy older adults were similar to those observed in the younger age group. However, only one breathing parameter was identified by the repeated measures ANOVA as being statistically significant; the regional contribution of the abdomen during the inspiration phase (%ABInsp; $F=3.53$, $df=1.92$, $p=0.04$). Like healthy younger adults, post hoc tests revealed that the differences were statistically significant between quiet breathing and speech, but not between any of the speech tasks. As in the younger age group, the regional contributions of the ribcage and abdomen appear to remain stable during speech, and the quiet breathing task was associated with a smaller abdominal contribution in comparison to the speech tasks. As previously discussed, this greater abdominal contribution observed during speech may be a result of the need to generate additional intra-abdominal pressure to sustain a prolonged expiration phase during speech (Hixon 1973).

In summary, the evidence in support of task specific breathing behaviours appears to be less consistent in healthy older adults. Reductions in respiratory muscle strength, which naturally occur with increasing age, may reduce the ability to generate adequate intra-abdominal pressure to modify speech breathing patterns in response to the type of speech produced.

8.3.3 Speech task specificity in chronic respiratory diseases

In the group of pooled patients with CRD (COPD and bronchiectasis), there was no evidence to suggest that speech breathing patterns were task specific between any of the tasks. Task specific breathing behaviours will now be discussed in relation to the pooled patients with CRD, followed by a discussion in relation to the individual pathologies studied in this research (COPD, bronchiectasis and self-reported asthma).

8.3.3.1 Pooled patients with CRD

Timing and volume parameters

Speech breathing patterns in pooled patients with CRD were significantly different from quiet breathing patterns, but were not task specific between the speech tasks. This is the first study to exclusively examine this feature in any patient group, so comparisons with previous literature are not possible. To date, 'task specific' breathing behaviours have only been reported from speech breathing patterns in healthy adults (Hoit et al. 1989; Sperry & Klich 1992; Winkworth et al. 1995; Wang et al. 2010).

In patients with chronic respiratory disease, the competition between speech and gas exchange needs has been shown to significantly reduce the time available for speech during the expiration phase. As a consequence, the inspiratory phase becomes prolonged (Loudon et al. 1988; Lee et al. 1993), 'distorting' the traditional 'saw-tooth' speech breathing pattern (Hodge & Rochet 1989). In healthy adults and healthy older adults, the unconstrained speech task (conversation) was associated with the longest expiratory phases, and it is likely that this was observed because participants were not restricted by pre-scripted grammatical boundaries. However, due to the distortion of the respiratory cycle caused by airflow limitation (Lee et al. 1993), it is possible that patients with CRD were unable to modify their speech, because a shortened expiratory phase was found during both the linguistically constrained and unconstrained tasks.

Other mechanisms could also reduce the ability to modify speech breathing in response to the type of speech (constrained or unconstrained), such as the presence of respiratory muscle weakness, which could reduce the ability to generate adequate sub-glottal pressure for the production of speech (Gosselink et al. 2011). Respiratory muscle weakness commonly manifests in the presence of airway obstruction, where respiratory muscle training is sometimes provided by physiotherapists to increase the strength of the respiratory muscles (such as the diaphragm) (Gosselink et al. 2011). It is also possible that age influenced task specificity. However, the data from adults who reported a history of asthma who were younger in age (mean age: 28.55 ± 6.15 years), suggested that their breathing patterns were not task specific. These findings will be discussed in more detail in section 8.6.2.

Regional contributions of the ribcage and abdomen

Ribcage and abdominal contributions were not task specific during speech in the group of pooled patients with CRD. However, in contrast to the healthy adults (young and old), the differences between quiet breathing and any of the speech tasks were also non-significant. To date there have been no published studies that have compared the regional contributions of the ribcage and abdomen between various breathing and speech tasks in patients with chronic respiratory disease, therefore no data are available for comparison. Physiologically, it is possible that significant differences in ribcage and abdominal movements were not observed between any quiet breathing or speech task in patients with CRD because of abnormalities in respiratory muscle recruitment, which is directly associated with airflow limitation (Peat et al. 1990; Roth 2008). Although airflow limitation is the hallmark of COPD (GOLD 2014), and is commonly seen in patients with bronchiectasis (Spruit & Singh 2013), respiratory muscle weakness often occurs as a secondary complication following prolonged hyperinflation (Frisk et al. 2014). It is therefore possible that patients with CRD could not significantly alter their chest wall movements in response to speech because of their diminished respiratory muscle strength (Cahalin et al. 2002). However, at present it is not possible to confirm these theories as respiratory muscle strength was not measured.

Speech task specificity will now be discussed according to individual pathologies; 1) COPD, 2) bronchiectasis and 3) adults with self-reported asthma.

8.3.3.2 Patients with COPD

When examining task specificity in patients with COPD, there was no evidence to suggest that speech breathing patterns were task specific. The findings from the repeated measures ANOVA identified one breathing parameter, inspiration time, as statistically significant ($F=13.67$, $df=3$, $p=0.00$). However, post hoc, pair-wise comparisons demonstrated that the differences were significant between quiet breathing and speech tasks (counting and reading), but not between any of the speech tasks. As discussed, no other studies have exclusively examined task specificity in patients with COPD. The observation that speech breathing parameters, particularly expiration time, could not significantly differentiate between quiet breathing and speech demonstrates the effect of respiratory impairment on breathing patterns, as five breathing parameters in healthy older

adults were able to significantly differentiate between speech and quiet breathing. Expiration time is the parameter which is most notably influenced by speech, where the expiratory phase is characteristically extended to increase the time available for speaking (Bunn & Mead 1971; Conrad & Schönle 1979). In contrast, the expiration phase during tidal breathing is typically shorter and proportional to the inspiration phase (Binazzi et al. 2006). Despite these behavioural adaptations to quiet breathing and speech, patients with COPD did not significantly extend their expiratory phase during the speech tasks. Some of the possible mechanisms for the inability for patients to extend their expiration phase have already been discussed in section 8.3.3.1. However another mechanism contributing to this observation could be related to the increased respiratory drive associated with a number of respiratory diseases, including COPD, which most commonly arises from hypoxia and hypercapnia (Erbland et al. 1990). This was indicated by the respiratory rate, which appears to be consistently faster during every breathing and speech task when compared to healthy older adults who completed each breathing and speech task under the same conditions. The impact of a faster respiratory rate directly affects breathing cycle time, by reducing the duration, as well as the duration of both the inspiratory and expiratory phase.

8.3.3.3 Patients with bronchiectasis

There was some evidence for task specificity in patients with bronchiectasis, as four breathing parameters were identified as statistically significant. In contrast to patients with COPD, the differences between speech tasks (counting and reading tasks) were found to be statistically significant for inspiration time and the regional contributions of the ribcage and abdomen during inspiration. However, the comparison between breathing tasks in patients with bronchiectasis was based on only four patients, so it is not possible to draw firm conclusions as the sample size was too small.

To the author's knowledge, breathing and speech breathing patterns have yet to be examined in patients with bronchiectasis, so direct comparison with other research was not possible. Research is therefore still required to examine task specificity in patients with bronchiectasis.

8.3.3.4 Self-reported asthma

There was some limited evidence to suggest that breathing behaviours were task specific in the group of adults with self-reported asthma. The findings from the repeated measures ANOVA identified statistically significant differences across the breathing and speech tasks for four breathing parameters. However, when examining the results from the post hoc tests, the pair-wise comparisons were only found to be statistically significant for one breathing parameter, inspiration time. Mismatches between a 'significant' ANOVA and non-significant post hoc test are not an uncommon finding, especially when some of the data are correlated (Rodger 1975). In the current research, post hoc tests were conducted using Bonferroni corrections for multiple comparisons, which have been considered to be more conservative than other post hoc tests, such as the Least Significant Difference (LSD) and Tukeys. This decision was made on the basis that six pairwise comparisons were being conducted, hence the type one error rate would increase to 30% without a statistical correction, which was considered to be unacceptable. The differences between the speech tasks were only found to be significant for one pair-wise comparison, between the describing and conversational speech task. However, since asthma status was not clinically confirmed, it is not possible to draw any firm conclusions from these findings. Due to the unconfirmed nature of their asthma, a decision was made to remove the data from these adults with self-reported asthma from the comparative analysis.

8.3.4 Summary of section 8.3

The findings from this research support previous observations of task specificity in healthy young adults. The novel finding is that this observation cannot be generalised to healthy older adults. Furthermore, there was no evidence to suggest that speech breathing patterns were task specific in patients with CRD, possibly indicating another mechanism which could be used to differentiate between health and disease.

8.4 The variability of breathing and speech breathing patterns

8.4.1 Breathing/ speech breathing variability in healthy younger adults and healthy older adults

Very few studies have reported on the variability of **speech breathing** patterns, because variability studies have primarily focused on **resting breathing** patterns (Tobin et al. 1988; Bruce 1996; Brack et al. 2002). Therefore limited published data are available for comparison.

The variability of breathing parameters at rest and during speech appeared to be similar for both healthy groups examined in this research (healthy young and older adults). This section will therefore discuss breathing/speech breathing pattern variability for both groups to avoid repetition. It was consistently observed that the variability of each speech breathing parameter was higher during the speech tasks when compared to quiet breathing. The variability of quiet breathing at rest has previously been reported to comprise a series of 'random' and 'non-random' components (Brack et al. 2002). While the non-random components are believed to represent autonomic control, such as tidal volume and ventilation, the random components are believed to be more influenced by cortical control, which enables individuals to engage in speech tasks (Brack et al. 1998). The observation that quiet breathing was consistently associated with the least variability is therefore not surprising because breathing cycles were not influenced by linguistic demand.

Within the speech tasks, no clear distinction was observed between the variability of the linguistically constrained (reading and counting) and unconstrained speech tasks (describing and conversational speech tasks). Since the unconstrained speech tasks were given linguistic freedom to alter and vary their sentences spontaneously and were not restricted by pre-scripted grammatical boundaries, it had been thought that speech breathing parameters measured during the linguistically unconstrained speech tasks might be associated with a greater variability. In a study by Conrad and Schonle (1979) with 15 healthy adults they reported that the variability of inspiratory and expiratory time was higher during a spontaneous speech task than during reading. However, the lack of any clear distinction between the variability of the

speech tasks suggests that speech task specificity might not be reflected by variability. The examination of absolute breathing parameters (such as mean inspiratory and expiratory time) may therefore be more useful than variability for examining speech task specificity in healthy adults

The breathing parameters associated with the expiratory phase (expiration time, expiration magnitude, %RCExp and %ABExp) were consistently associated with greater variability during the speech tasks than quiet breathing. Since speech is produced in the expiratory phase of the breathing cycle (Hixon 1973; Hodge & Rochet 1989), changes in the length of the sentences spoken in the expiratory phase may have accounted for this greater variability. The variability of the abdominal contribution to inspiration and expiration was consistently greater (more than twice as high) than the variability of the ribcage contribution. This trend was observed during every breathing and speech task, in healthy older and younger adults. Generation of sub-glottal pressure for the production of speech is achieved by net compression of the lungs which can be achieved by a range of ribcage and abdominal contributions. However, abdominal muscle activity has been shown to be greater during speech (Hixon et al. 1973), which could account for why the variability of the abdominal contribution during speech was greater than the ribcage contribution.

8.4.2 Breathing/speech breathing variability in pooled patients with CRD

No clear difference between the variability of quiet breathing and speech was observed in the data from the group of pooled patients with CRD. Furthermore, when compared to the data from healthy older adults, patients with CRD had greater variability for every breathing parameter during quiet breathing, apart from expiration time. The benefit of monitoring **resting** breathing pattern variability is well recognised. Measurements of variability are frequently used in the context of 'stability' or 'instability', and abnormalities in the control of breathing resulting from breathing pattern instability have been associated with a number of respiratory complications (Khoo 2000). Low tidal volume breathing variability has been associated with pathological disease (Brack et al. 2002), chemically induced respiratory loading (Brack et al. 1998), and has been used as a predictor of unsuccessful patient separation from mechanical ventilation (Wysocki et al. 2006). On the other hand, a number of respiratory conditions have been associated with abnormally high variability and reduced stability

during resting breathing. For example, Cheyne-Stokes respiration is a distinctive breathing pattern often seen in patients with end stage congestive heart failure, and is characterised by periods of rapid breathing, followed by intermittent periods of apnoea (Andreas et al. 1996). Therefore, this pattern of breathing has high variability, reduced stability, and its presence has been associated with a higher risk of patient mortality (Andreas et al. 1996; Hanly & Zuberi-Khokhar 1996). Thus it seems that there is an optimal level of breathing pattern variability, with either too low or too high being associated with disease.

In the pooled CRD group the variability of breathing parameters associated with the expiratory phase had greater variability than during the inspiratory phase. As already discussed, this is likely to be related to change in the length of sentences spoken in the expiratory phase. No consistent pattern of difference in variability was observed between healthy older adults and patients with CRD for any parameters relating to respiratory timings or magnitudes during the speech tasks. However, patients with CRD consistently produced a higher ribcage and abdominal variability compared to healthy older adults during quiet breathing and every speech task. Patients with COPD have a number of structural abnormalities such as reductions of elastic recoil and respiratory muscle strength (O'Donnell & Laveneziana 2006; Loring et al. 2009). These abnormalities could mean that they are unable to maintain a consistent ribcage and abdominal displacement during quiet breathing and speech, and therefore have greater variability associated with their chest wall movements. Based on the concept that respiratory disorders are associated with high levels of resting breathing pattern variability (Andreas et al. 1996; Khoo 2000), it is possible that this theory could also apply to speech breathing patterns, as was found in this research. These findings suggest that examining the variability of the regional contributions of the ribcage and abdomen during speech might be useful for detecting abnormalities in lung health, compared to healthy individuals.

8.5 The influence of age and sex on breathing and speech breathing patterns in healthy adults

The paucity of research into speech breathing patterns has meant that the influence of age has received little attention, and there is no consensus on whether age has a significant influence on these patterns (Hoit & Hixon 1987). In contrast, the influence of age on breathing mechanics during **resting breathing**

has been extensively researched (Janssens et al. 1999; Pride 2005; Watsford et al. 2007). One of the age related changes in respiratory mechanics is chest compliance, which has repeatedly been shown to decrease with increasing age (Mittman et al. 1965; Lanteri & Sly 1993; Janssens et al. 1999). Reductions in elastic recoil have been shown to account for these differences (Lalley 2013).

Research examining the influence of sex on breathing patterns has also been limited. Sex related differences in breathing mechanics have been previously related to developmental differences, for example surfactant deficiency in neonates is more commonly found in males, as the production of surfactant has been shown to occur earlier in females (Fleischer et al. 1985). Anatomical differences, such as the size of the thorax and chest wall circumference have also been thought to account for the documented differences in resting lung function (Verschakelen & Demedts 1995; Carey et al. 2007). Anatomical differences have been shown to account for the observed differences in speech breathing patterns between male and females, however these studies measured breathing patterns using dated methods, where breathing cycles were identified from segments of speech played through a cassette player (Hoit et al. 1989; Sperry & Klich 1992).

There is no clear consensus regarding whether age or sex have any significant impact on breathing and speech breathing patterns when measured using newer, automated methods. It therefore was considered important to examine this possibility further, as these variables could influence the interpretation of the results in speech breathing studies, particularly when performing comparative analyses. In this research the issue has been addressed using two approaches: by making direct comparisons between the younger and older healthy adult groups, and by using multiple regression analysis on the pooled data from the two healthy adult groups (older and younger).

8.5.1 The influence of sex

In these data, sex was not found to have a significant influence on any of the breathing parameters, during any of the tasks. Previous small observational studies also reported that respiratory timing parameters were not significantly influenced by sex, although there was some suggestion that breathing pattern was more 'costal' in females, compared to males during reading and singing

(Binazzi et al. 2006). While these findings were based on chest wall measurements obtained using OEP, similar findings have also been documented using different measurement systems. For example, movements of the chest wall were measured using a three-dimensional motion system (Vicon worksystem) to track the displacement of 14 markers positioned on the thorax and abdomen during quiet breathing in 100 healthy adults (Kaneko & Horie 2012). Abdominal displacements during tidal breathing were found to be greater in the males. Another study (n=10) using RIP suggested that the abdominal contribution to tidal breathing was greater in males than in females during conversational speech and reading (Hodge & Rochet 1989). However, in their study, the differences in chest wall displacements were thought to reflect the differences in chest wall size, rather than sex. Therefore, the finding here that sex had no significant influence on breathing and speech breathing patterns supports the existing theory that the task requirements of speech have a greater functional role than sex in determining normative speech breathing behaviours (Hodge & Rochet 1989).

8.5.2 The influence of age

There was a small indication that the variance of expiration time during the **quiet breathing task** could partly be explained by age, where the beta weights showed that a unit increase of one year was associated with a predicted increase of 0.01 seconds. However, while the overall fit of the model was found to be statistically significant ($p=0.01$), the correlation was found to be weak ($R^2=0.12$), and was not found during any of the speech tasks. The findings from the independent t tests also indicated that expiration time measured during the quiet breathing task was significantly longer in healthy older adults when compared to younger adults ($t=-4.42$, $df=3$, $p=0.00$). However, as for the regression analysis, these significant findings were confined to the quiet breathing task. The idea that expiration time might increase with age appears to be counter intuitive, since studies examining the influence of age on breathing mechanics have repeatedly shown that increasing age is negatively associated with breathing mechanics (Lanteri & Sly 1993; Pride 2005; Watsford et al. 2007). In particular, reductions in elastic recoil and respiratory muscle strength would theoretically mean that the ability to sustain the expiration phase would also decline with age (Lalley 2013).

Age was found to significantly influence chest wall contributions (regional contributions of the ribcage and abdomen to inspiration and expiration) consistently during every task ($p=0.00$). In general, the regression analysis suggested that increasing age was associated with a greater ribcage and smaller abdominal contribution. However, the correlation was again found to be weak. The comparative analysis presented in section 7.5.5 also indicated that ribcage contribution during expiration was significantly greater in healthy older adults during every breathing and speech task. Few studies have compared the regional contributions of the ribcage and abdomen during quiet breathing and speech between young and old age groups. Of the few, a similar study using RIP also demonstrated a trend towards a greater ribcage contribution during quiet breathing in the supine position. Tobin *et al* (1983) measured resting breathing patterns in 18 older adults (mean age= 68.9 ± 6.5 years) and 47 healthy young adults (mean age= 28.6 ± 5.3 years). While comparisons were not performed using statistical tests, their findings also suggested that ribcage contribution during tidal breathing was greater in healthy older adults ($46\pm 14\%$) when compared to the younger group ($42\pm 3\%$). Physiologically, a trend towards a breathing pattern that is dominated by rib cage displacements with increasing age could be partly explained by age related changes in respiratory muscle postural strength. In particular, diaphragmatic strength has been shown to be reduced in older individuals (Tolp *et al.* 1995), increasing the contribution of the ribcage compartment during tidal breathing. A trend towards an increased ribcage contribution with increasing age is also likely to be related to age related change in respiratory mechanics (Janssens *et al.* 1999; Watsford *et al.* 2007). However, the ribcage contribution observed throughout every task in healthy older adults in the current research was even higher than expected (between 82 and 84%). At present it is not known why the ribcage contribution was found to be so high in the healthy older group in comparison to the Tobin *et al* (1983) data, but may reflect methodological differences. As previously mentioned, one of the challenges faced when interpreting breathing and speech breathing parameters (such as regional contributions of the ribcage and abdomen) is concerned with the lack of well-defined normative reference values that have been obtained using standardised protocols.

The findings from the independent t tests (section 7.5.5) indicated that expiration magnitude was significantly larger in the healthy younger adults than

the healthy older adults, throughout every breathing and speech task. While these findings cannot be directly compared to existing literature (as respiratory magnitudes have not previously been quantified as a surrogate for tidal volumes), these findings further reflect the influence of increasing age on respiratory mechanics during quiet breathing and speech. Physiologically, the effect of ageing on the respiratory system is associated with reduced lung compliance and increased residual volume, which reduces volume of air entering and exiting the lungs during tidal breathing (Lanteri & Sly 1993). This was reflected in the current research, as healthy older adults had a significantly smaller expiration magnitude when compared to the younger group during every breathing and speech task. However, no firm conclusions can be drawn from these findings as the regression analysis did not identify any significant influence of age on expiratory magnitude, and the t test results were based on a sample of small size, which may not be representative of the wider population.

8.5.3 Summary of section 8.5

In summary, breathing and speech breathing patterns seem to be influenced by age, but not sex. Age was therefore taken into consideration during the comparative analysis (in section 7.5.7), where a decision was taken to compare breathing and speech breathing pattern data between healthy older adults and pooled patients with CRD.

8.6 The influence of chronic respiratory disease on breathing and speech breathing patterns

The influence of chronic respiratory disease on breathing and speech breathing patterns will now be discussed according to the following sub-headings; 1) COPD *versus* bronchiectasis, 2) Self-reported asthma *versus* healthy younger adults, and 3) healthy older adults *versus* pooled patients with CRD.

8.6.1 COPD *versus* bronchiectasis

In this research no statistically significant differences in timings, relative volumes or chest wall movements were detected between COPD and bronchiectasis patients during any task. This was the first study to record

speech breathing patterns in patients with bronchiectasis. One previous study looked for differences in speech breathing patterns between different diagnostic groups, where it was concluded that speech breathing patterns were significantly different (asthma ($n=14$), emphysema (COPD) ($n=15$), sarcoidosis ($n=12$) and healthy individuals ($n=14$)) (Lee et al. 1993). Lee *et al* (1993) used discriminant function analysis to identify two breathing parameters that best predicted group membership; inspiratory time/total time and expiratory time. They reported that 54% of the overall participants were classified correctly according to their primary diagnosis, which means 46% were not. This sounds close to the 50:50 expectation from tossing a coin. On closer inspection, healthy participants were correctly classified more frequently (69%), while sarcoidosis had the fewest correct classifications (25%). Although patients with emphysema (COPD) were correctly classified 60% of the time, these patients were the most physiologically impaired (FEV_1 %predicted = 42.5 ± 13.1), compared to the asthma (FEV_1 %predicted = 70.0 ± 20.5), sarcoidosis (FEV_1 %predicted = 79.5 ± 7.49) and healthy participants (FEV_1 % predicted = 78.3 ± 7.85), who all appeared to have similar lung function. Therefore, although the authors described speech breathing patterns as being ‘disease specific’, their findings could just mean that speech breathing patterns differed between healthy people and those with severe respiratory impairment, rather than between specific diseases.

In this research, patients with COPD and bronchiectasis had similar ages and lung function. It is possible that significant differences in breathing parameters were not observed between the two diagnostic groups because both groups had similar lung function, as they were both classified as having ‘severe’ airways obstruction according to the GOLD classification of airways obstruction guidelines (GOLD 2014). It is also possible that statistically significant differences were not detected between the two diagnostic groups because the sample size was too small. Retrospective power calculations based on respiratory rate suggest that a sample size of 2982 (1491 per group) would be required to detect a statistically significant difference at the 0.05 alpha level in a future study, at 80% power (see appendix 3).

8.6.2 Self-reported asthma *versus* healthy younger adults

No statistically significant differences were identified between healthy younger adults ($n=29$) and adults with self-reported asthma ($n=11$) for any breathing

parameter or task, apart from expiration time. Expiration time was found to be significantly longer in the asthma group during the quiet breathing task (mean difference: 1.12 sec., $t=-4.08$, $df=38$, $p=0.00$). This finding appears to be counter intuitive. Physiologically, patients with asthma commonly present with persistent airflow limitation which arises from chronic airways inflammation and is marked by reductions in Peak Expiratory Flow (PEF) (chapter three) (Lopez & Del Castillo 2000; John Henderson 2013). Airflow limitation can be variable and fully reversible. However, in some patients persistent airflow limitation can develop, despite optimal treatment (Barnes & Woolcock 1998). In theory, the presence of airflow limitation would also impact respiratory timing components, by reducing their duration.

Although the differences between the two groups were non-significant during the speech tasks, adults with self-reported asthma consistently produced a breathing pattern that was characterised by having a longer inspiration phase, shorter expiration phase, smaller expiratory magnitude and a faster respiratory rate when compared to healthy younger adults. It is possible that the small sample size was insufficiently powered to detect a significant difference between the two groups. Retrospective power calculations based on respiratory rate indicate that a sample size of 90 participants (45 in each group) would be required to detect a significant difference at the 0.05 alpha level, at 80% power (see Appendix 3). However, a trend towards a significantly longer inspiration phase, and shorter expiration phase in patients with asthma has previously been documented in a previous study which was also based on a small sample size (Loudon et al. 1988). As previously discussed in the literature review (section 5.4.3), Loudon *et al* (1988) compared the breathing patterns obtained using RIP during conversation, describing and counting between healthy adults ($n=10$) and patients with varying degrees of asthma ($n=14$). Amongst the major findings of their study, patients with asthma were found to spend a significantly greater proportion of the respiratory cycle on the inspiration phase, while their expiration phase was shorter, and respiratory rate faster when compared to healthy adults. At present it is not possible to draw any firm conclusions from the findings in the current research because asthma status was not clinically confirmed, and was self-reported.

Due to the uncertainties regarding asthma status in the current research, a decision was made to exclude adults with self-reported asthma from the pooled

analysis (in the next section) on the basis that 1) their diagnosis was unconfirmed, and 2) they were younger in age.

8.6.3 Pooled CRD vs healthy older adults

The breathing and speech breathing patterns that were obtained from participants with COPD and bronchiectasis were pooled into one group to increase the power of the sample (n=20). This group was compared to the older healthy group (n=20).

A study by Lee *et al* (1993) has concluded that speech breathing patterns differed between health and disease. However, in their sample, patients with emphysema (COPD) had an average age of 62.5 ± 8.98 years and were compared to healthy adults with an average age of 39.8 ± 14.0 years (Lee et al. 1993).

It is possible that the differences observed in the study by Lee *et al* (1993) could partly be explained by the age difference, since the average age difference between the two groups was 23 years. In this research the average age difference between the two groups (healthy older and COPD/bronchiectasis) was only 3 years, which was non-significant.

8.6.3.1 Respiratory timing and magnitude parameters

In comparison to the healthy older group, patients with CRD consistently produced speech breathing patterns that were characterised by having longer inspiratory timing, shorter expiratory and breathing cycle timings, smaller respiratory magnitudes and a faster respiratory rate during every speech task. The next sections will discuss the results from the independent sample t tests based on expiratory magnitude, expiratory time, respiratory rate and the regional contribution of the rib cage to expiration.

Respiratory volumes (Expiratory magnitude)

There were no statistically significant differences in expired volumes (magnitudes) between healthy adults and pooled patients with CRD during any of the tasks examined. This lack of statistical significance could have resulted from a small sample size (see appendix 3). Retrospective power calculations based on expiratory magnitude indicated that a sample size of 142 (71 per

group) would be required to detect a statistically significant difference in a future study, at the 0.05 alpha level (80% power).

While respiratory magnitudes have not been quantified in previous speech breathing studies, Lee *et al* (1993) estimated the volume of air expired as a percentage of the vital capacity using RIP in 16 healthy adults and 15 patients with COPD during a conversational speech and counting task. Although the differences between the two groups were not directly compared for statistically significant differences, the volume of expired air (%VC) in patients with COPD and healthy adults was reported as $22.0 \pm 16.3\%$ and $14.2 \pm 9.9\%$ respectively during a conversational speech task. Similar findings were also reported during a counting task for patients with COPD (expired volume %VC = 26.3 ± 16.1) and healthy adults (expired volume %VC = 10.1 ± 8.1). These findings indicate that patients with COPD use a greater percentage of their vital capacity during speech. The use of higher lung volumes in patients with COPD may be a compensatory mechanism to increase the static lung recoil. Loss of elastic recoil pressure in the small airways is a consequence of hyperinflation, which leads to reduced pressure in generating expiratory flow (O'Donnell & Laveneziana 2006). Therefore, patients with COPD have been shown to initiate breaths at higher volumes to increase the calibre of their airways (Loudon et al. 1988). However, as previously noted, the findings from Lee *et al* (1993) are not conclusive because of the large age difference between their sample of healthy adults (mean age: 39.8 ± 14.0 years) and their sample of patients with COPD (mean age: 62.5 ± 8.98 years). Age related influences on volumes could have been larger than respiratory pathology influences.

Respiratory timing (Expiration times)

Statistically significant differences in expiratory times were detected between healthy older adults and patients with CRD during the conversation and reading task, but not during the counting or quiet breathing tasks. Expiratory flow limitation during **tidal breathing** has been associated with severe obstructive airways disease (Baydur & Milic-Emili 1997; GOLD 2014), while expiration time emerged as the best parameter to predict respiratory disease group membership during **spontaneous speech** (Lee et al. 1993). Physiologically, reductions in the duration of expiration may be a direct consequence of airways obstruction,

which has been considered to be the hallmark of COPD (Spruit & Singh 2013; GOLD 2014), and is also a characteristic of patients with bilateral bronchiectasis and other obstructive disease (Baydur & Milic-Emili 1997; Koulouris et al. 2003). As discussed, Lee *et al* (1993) also reported that expiratory time was significantly shorter in patients with emphysema (now defined as COPD) during a counting and conversational speech task. However, as with their volume results, it is not clear whether age or pathology had more influence on expiration time (Hoit & Hixon 1987; Pride 2005; Watsford et al. 2007). The findings from the current research provide a clearer indication about the influence of respiratory disease on expiratory time during speech, because the age difference between the two groups in the current research was small and non-significant. This was the first study to have examined speech breathing patterns in patients with CRD during a reading task, so comparisons with published data are not possible, but no influence of disease on expiratory time was seen during the reading task.

The mean difference in expiratory time between the groups was smallest during the quiet breathing task. Unlike speech, quiet breathing does not impose any additional mechanical demand on respiratory drive (Bailey & Hoit 2002; Hoit et al. 2007). The dual-task of producing speech while satisfying ventilatory needs has been shown to cause speaking related breathlessness during high respiratory drive (for example, during exercise) in healthy adults (Bunn & Mead 1971; Hoit et al. 2007), while patients with chronic respiratory disease have been shown to exhibit speaking related breathlessness in the absence of any external mechanical load (Lee et al. 1993). The finding that the size of difference in expiration time was the smallest during the quiet breathing task provides further support for the hypothesis that breathing patterns during speech may be more useful than resting breathing for highlighting any differences between health and respiratory disease.

The mean difference between the two groups for expiratory time was found to be the greatest during the conversation task which was statistically significant. Linguistically, a spontaneous speech task, like conversational speech, provides patients the ventilatory freedom to adjust their speech within a comfortable range to avoid breathlessness, as conversational speech does not imposed any pre-scripted grammatical boundaries (Winkworth et al. 1994; Winkworth et al. 1995). Participants had the freedom to pause, or alter their speech in response

to any respiratory discomfort (Lee et al. 1993). In contrast, the reading task cued participants to breathe and pause in response to pre-written grammatical boundaries in the text. Since both groups were provided with the same reading material, the grammar and pre-written text may have caused both groups to pause and breathe at the same locations throughout the recording. Previous research has reported that breaths are taken at grammatically appropriate locations (Winkworth et al. 1994). However, these theories cannot be confirmed as the linguistic locations of breaths were not examined in this research, because the aim was to produce an automated system, and computers are not yet able to cope with semantic analysis of running speech.

Respiratory rate

Statistically significant differences in respiratory rate were only identified between the two groups during the conversational speech task, where pooled patients with CRD were found to have a significantly faster respiratory rate in comparison to healthy older adults ($t=-2.87$, $df=37$, $p=0.00$). Physiologically, a faster respiratory rate manifests from the increased respiratory drive secondary with chronic airflow limitation (Sassoon & Hawari 1999; Scano & Ambrosino 2002).

While the trend towards a faster respiratory rate was also observed within the patient group during the reading, counting and quiet breathing task, the differences between the groups were non-significant. As previously discussed, the lack of statistical significance could be because the sample size lacked statistical power. Retrospective power calculations based on respiratory rate suggest that a future study would require a sample size of 90 (45 per group) to detect a statistically significant difference at the 0.05 alpha level, at 80% power (see Appendix 3). However, since the differences between the groups were found to be statistically significant during the conversational speech task, this finding provides further evidence to suggest that a conversational speech task may be more useful for highlighting the difference between health and disease. As previously discussed, a conversational speech task allowed patients to alter their breathing pattern within a comfortable range, in response to their airflow limitation. This could have meant that the differences between health and disease appeared to be more profound during the conversational speech task because the task allowed patients the freedom to alter their breathing cycles.

8.6.3.2 Regional contributions of the rib cage and abdomen

This was the first research to explore chest wall contributions during speech breathing in a patient sample. To date the limited evidence that speech breathing patterns differ between healthy adults and patients with chronic respiratory disease has been based solely on respiratory timing and volume components (Loudon et al. 1988; Lee et al. 1993). No previous research has quantified regional contributions of the ribcage and abdomen during speech tasks in patients with CRD, even though abnormalities in chest wall movements have been repeatedly documented during tidal breathing (Delgado 1982; Gilmartin & Gibson 1984; Georgiadou et al. 2007).

It is generally believed by clinicians that the presence of chronic respiratory disease is associated with a characteristic 'apical' breathing pattern, with minimal abdominal displacement, especially in the advanced stages of the disease pathway (De Troyer et al. 1997; GOLD 2014). In turn, physiotherapy practices such as 'breathing retraining' provide techniques to optimise the use of the diaphragm, by providing exercises to recruit abdominal activity during inspiration, while relaxing the shoulders to improve ventilation (Casciari et al. 1981; Dechman & Wilson 2004). Physiologically, diaphragmatic insufficiency (which arises from hyperinflation) places patients with COPD at a mechanical disadvantage during tidal breathing, because it decreases the ability of the lungs to generate inspiratory pressures (Frisk et al. 2014). In COPD there is increased activity of the accessory muscles of respiration in order to generate enough pressure to expel the air (Similowski et al. 1991; Ottenheim et al. 2005). As a consequence, a number of clinical descriptors have been used to describe the breathing pattern that arises from diaphragmatic insufficiency, such as 'apical breathing' and 'use of accessory muscles'.

In this research the percentage contributions of the rib cage and abdomen during inspiration and expiration appeared to be counterintuitive when comparing between healthy older adults and patients with chronic respiratory disease. Healthy older adults used a significantly greater proportion of ribcage motion, and hence a smaller proportion of abdominal motion, during inspiration and expiration when compared to patients with CRD. The differences for %RCExp was found to be statistically significant between the two groups for every task. However, these findings contradict standard text book descriptions and the

common clinical belief that patients with respiratory disease recruit a smaller proportion of their abdominal muscles during tidal breathing in comparison to healthy adults (Binazzi et al. 2008).

As this was the first study to include these parameters during speech breathing tasks, comparisons with previous literature are not possible. Of the few studies that have quantified the regional contributions rib cage and abdomen **during tidal breathing**, there is some evidence to suggest that patients with COPD have a 50:50 rib cage to abdomen contribution, with a move towards a more abdominal breathing pattern during exercise. In a previous study which employed RIP to measure breathing patterns from 22 males with 'stable' COPD (FEV_1 % predicted = 42.6 ± 13.5), resting rib cage and abdominal contributions to tidal volume were reported to be $49.82 \pm 11.19\%$ and $50.18 \pm 11.19\%$ respectively (Alves et al. 2008). In the current research it was around 60:40.

One of the reasons for the discrepancies between these findings could be related to the system used to measure breathing pattern. Breathing pattern data from this research, as well as in the study by Alves et al (2008) were obtained using RIP. Using the two degrees of freedom model proposed by Konno and Mead (1967), RIP measures the change within the cross sectional area of the thoracic cavity. As previously discussed in section 2.3.5.1, embedded within the model was the assumption that the chest is made from two 'cylinders': a ribcage and an abdominal compartment. In a RIP system bands are placed around each of these compartments. The rib cage band is placed just below the axilla, representing the lower part of the rib cage. While RIP claims to quantify ribcage activity, the actual measurement is taken only from the lower ribcage. This provides no information about the movement of the upper ribcage, which has been traditionally identified as the area more likely to be used in chronic respiratory disease (GOLD 2014). Furthermore, due to its anatomical low positioning, it is possible that the ribcage band could also be influenced by some abdominal movement. The counterintuitivity of the findings in this research could therefore be attributed to the positioning of the bands and the different uses of medical terminology conflicting with what is measured by RIP. For example, 'apical breathing' anatomically refers to the area around the clavicles, whereas the RIP ribcage band measures the changes in the cross sectional areas in the lower chest. Nevertheless, these findings suggest that patients with chronic respiratory disease do not exhibit a breathing pattern dominated by

ribcage movement, contradicting standard text book descriptions and clinician perceptions. At present it is not known why healthy older adults had a greater ribcage contribution during tidal breathing and speech, but the methods and procedure used to obtain data from both groups were the same. This included the calibration procedures, positioning of the RIP bands, recording period (two minutes) and the speech tasks.

8.6.4 Summary of section 8.6

Expiratory time, respiratory rate and %RCExp were found to be significantly different between healthy older adults and patients with CRD during every breathing and speech task. However, the greatest number of significant differences was observed during the conversational speech task. A conversational speech task may therefore be more useful for highlighting the differences between health and disease during future speech breathing assessments because the task allows patients to alter their breathing pattern in response to their airway limitation. Future research is needed to quantify the regional contributions of the ribcage and abdomen during speech in patients with CRD, in order to provide comparative data.

8.7 The responsiveness of breathing and speech breathing patterns to a clinical intervention (Pulmonary Rehabilitation) for patients with COPD or bronchiectasis

If speech breathing patterns are to have any value for monitoring chronic respiratory disease progress, it would be useful to know if they are responsive to change. In this research a decision was made to look for proof of principle data via an observational study of an existing clinical intervention (pulmonary rehabilitation (PR)). PR was selected on the basis that it has a robust evidence base for effectiveness in chronic respiratory disease (Lacasse et al. 2007; BTS 2013), and frequently contains breathing pattern manipulation as part of the programme (NICE 2010; Spruit & Singh 2013).

Breathing and speech breathing pattern data were recorded before, during and after a six week PR programme. Data on some clinical variables were obtained from the medical notes.

The main findings were:

1. No changes in resting breathlessness (Borg scores) were detected after PR.
2. Functional walking distance increased significantly (both clinically and statistically) after PR.
3. No changes in breathing and speech breathing parameters in the pooled patients with chronic respiratory disease were detected after PR.
4. No changes in the variability of breathing parameters in pooled patients with chronic respiratory disease were detected after PR.

These findings will now be discussed.

8.7.1 Breathlessness

The level of self-perceived breathlessness did not change significantly between the baseline and post PR assessment. Previous studies that have reported a significant level of improvement had a high level of breathlessness at baseline (>5) (Gigliotti et al. 2003; Clini et al. 2009), whereas in this research the average resting Modified Borg Score for the group was very low at baseline ('very mild shortness of breath') and remained low after the six week PR programme, and no statistically significant changes were detected. It is therefore likely that significant changes in breathlessness were not seen because of a 'ceiling effect'. This means that since the average Modified Borg Score was already low at baseline, there was no room for further improvement, even after a six week PR programme (Wang et al. 2008).

Several studies that have observed significant improvements in Modified Borg Scores following PR have reported higher breathlessness scores at baseline (Foglio et al. 1999; Ries 2005; Lacasse et al. 2007; Clini et al. 2009). Foglio *et al* (1999) examined the long term effectiveness of PR in 32 patients with COPD before and after an eight week PR programme which included optimisation of pharmacological medicine and three, three-hourly sessions of supervised incremental exercises per week. While the intensity of the PR intervention was

much higher than the PR programme in this research, the average baseline Modified Borg Score was reported to be 5.4 ± 1.3 , which significantly reduced to 3.6 ± 0.9 following the eight week intervention. Similar Modified Borg Scores have also been reported in other studies at baseline; 6.4 ± 1.6 (Clini et al. 2009) and 6.6 ± 2.6 (Gigliotti et al. 2003). Given the limited number of studies that have used the Modified Borg Score to evaluate breathlessness following PR, the minimal clinically important difference (MCID) remains uncertain, although Ries *et al* (2005) suggests that changes of two units are most commonly observed and associated with large effect sizes (above 0.8) as defined by Cohen (1992) (Cohen 1992a; Ries 2005). In this research the baseline Modified Borg Score was already too low for any change to be deemed as ‘clinically significant’.

The subjective nature of the Modified Borg Scale

One of the limitations of the Modified Borg Scale as an outcome measure relates to its subjectivity. Poor symptom perception has been widely acknowledged in a range of chronic respiratory diseases (Janssens et al. 2009), and has been considered to be an important factor in COPD morbidity and mortality related to poor treatment outcomes (von Leupoldt & Dahme 2007). The sensation of breathlessness is a subjective experience (Cockcroft & Guz 1987; Burdon et al. 1996; Ambrosino & Scano 2001) and the Modified Borg Scale requires the individual to rate this experience on a ten point scale anchored to descriptions ranging from “nothing at all” to “shortness of breath so severe you need to stop” (Chen et al. 2002). A number of psychological and emotional factors have been shown to influence the perception of breathlessness (Burdon et al. 1996), and focusing attention away from breathlessness has been shown to reduce the level of perceived breathlessness (Thornby et al. 1995). Nevertheless it has been reported that the Modified Borg Scale is a reliable and valid tool in pulmonary medicine (Chen et al. 2002; Ries 2005).

8.7.2 Functional exercise capacity (Incremental Shuttle Walk Test)

The minimal clinically important difference (MCID) for the ISWT has been previously described in two papers (Singh et al. 2008; Dodd et al. 2011). In the original paper by Singh *et al* (2008), a change of 47.5m (5 shuttles) was associated with feeling ‘slightly’ better, while a change of 78.7m (eight shuttles) was associated with the next rating “better”. The average improvement in walking distance that was observed in this research exceeded both of these

thresholds, as walking distance was found to improve by an average of 89m for the group. This improvement is higher than the level of improvement documented in some previous studies. In a previous observational study where 395 patients with COPD attended an eight week outpatient PR based programme, the mean (95% CI) improvement after PR was 66m (5-83) in patients with and MRC grade of 2, and 55m (43-64) in patients with grade 5, where both grades were found to be significant ($p < 0.0005$).

In another study where the efficacy of an 'intensive' eight week PR programme was examined in an RCT of 126 patients with COPD, ISWT distance was also found to significantly improve by 88m in patients who had 'moderate' symptoms based on the MRC scale (3 and 4), while patients with a 'severe' rating of breathlessness (MRC grade 5) improved by only 10m, which was under the MCID threshold. However, in their study, patients with an MRC score of 5 (severe) had supervised training at home, while patients with 'moderate' breathlessness had supervised training within an outpatient setting, which was not accounted for by the trial. These findings suggest that improvements in ISWT distance decrease with increasing MRC grade (Wedzicha et al. 1998; Singh et al. 2008). In this research MRC scores were not available, but the low baseline Borg scores could explain why the level of improvement exceeded the changes in walking distances that were documented by previous studies. However, while the average change in walking distance was deemed as clinically and statistically significant, the wide confidence interval suggests that there was high variance between the subjects. The individual data demonstrates that two participants increased their walking distance by an average of 250m, although walking distance was found to decrease post PR for only one participant (PR3).

The ISWT is a standardised measure for evaluating endurance capacity in patients with chronic lung disease during submaximal exercise (such as activities of daily living) (Revill et al. 1999; Eaton et al. 2006; Holland et al. 2014). However, while the test aims to measure functional walking distance, the test is effort dependant and is subject to non-respiratory limitations, such as weakness or pain (Hill 2006). It is possible that participant PR3 had a shorter walking distance after PR because s/he had one or more of these non-respiratory limitations. However this information was not recorded in the patient notes and it is therefore not known if the decrease in walking distance was due to a)

deteriorating respiratory symptoms b) the onset of a non-respiratory limitation (such as pain) or c) another reason.

There is also some evidence to suggest that patients worked harder during the ISWT after the six week PR programme. This is because the mean heart rate for the group measured immediately after the ISWT was found to increase significantly after the six week PR programme. Breathlessness scores were also higher post ISWT, post PR, although the difference did not reach statistical significance. The ISWT was originally developed to overcome some of the practical issues associated with traditional outcome measures, such as cycle ergometry and treadmill testing, because it is thought that these methods are not representative of naturalistic daily exercise (Spence et al. 1993; Holland et al. 2014). While the ISWT is believed to overcome these issues, reproducibility studies have highlighted the risk of a learning effect (Knox et al. 1988; Dyer et al. 2002). In these studies, test re-test results indicated that performance improved when carried out over consecutive days and weeks. It is therefore recommended that two baseline tests are performed to overcome any possible training effect (Holland et al 2014). However, the PR programme observed in this study only performed a single test at baseline. A learning effect can therefore not be ruled out, and may account for some of the large improvement in the ISWT seen from before to after PR.

8.7.3 Breathing and speech breathing patterns

8.7.3.1 Respiratory timings and magnitudes before and after PR

No clinically or statistically significant changes in breathing parameters relating to respiratory timings and magnitudes in pooled patients with CRD were detected after PR. This is the first study to compare respiratory timing and volume components before and after a PR programme for patients with COPD and bronchiectasis, so no data are available for comparison. Randomised controlled trials have repeatedly shown that PR reduces breathlessness and increases exercise tolerance (Reardon et al. 1994; Couser et al. 1995; Griffiths et al. 2000; Berry et al. 2003), improves health related quality of life (Wijkstra et al. 1995), reduces hospital admissions and reduces re-admission in patients with COPD (Morgan 2003) compared to those receiving 'usual care'(Lacasse et al. 2007; BTS 2013). However, PR has been found to have minimal effect on lung

function, as airways limitation persists throughout the natural history of COPD (Lacasse et al. 2007; Ries et al. 2007). PR has also been found to significantly reduce speaking related breathlessness (Binazzi et al. 2011), which is directly related to specific parameters of breathing pattern, such as respiratory timing components and volume. However, as previously discussed in section 5.4.2, it is possible that these results were influenced by the high intensity of the exercise component (six sessions per week for a period of four weeks). Therefore, it is not clear if speaking breathlessness would reduce following a typical PR programme which is much lower in intensity.

Regional contributions of the rib cage and abdomen

No changes in relative ribcage and abdominal contributions to respiration were detected after PR. This was the first study to record these parameters during speech tasks before and after any clinical intervention. In theory, data relating to the movements of the chest wall could provide important sources of information relating to respiratory health (Gilmartin & Gibson 1984; Aliverti et al. 2004; Binazzi et al. 2008), and have potential in the evaluation of physiotherapy interventions in patients with breathing dysfunction. However, while a number of strategies used within traditional PR programmes aim to improve the mechanics of breathing, such as breathing retraining techniques, there is still no evidence that the contributions of the rib cage and abdominal compartments alter following PR.

In a recent study by Georgiadou *et al* (2007), regional ribcage and abdominal volumes were examined in patients with COPD in order to understand the mechanisms of improvement in chest wall modulation following exercise. Using OEP, the separate compartmental volumes of the rib cage and abdomen were quantified at rest, as well as during an exercise test protocol (three minutes of rest, followed by three minutes of unloaded pedalling). These measurements were obtained before and after participants attended a 12 week PR programme, with participants attending three sessions per week. It was reported that PR which predominantly consisted of physical exercise was associated with significant reductions in dynamic hyperinflation. End-expiratory abdominal volumes were found to reduce significantly both at rest and during exercise (163 ± 59 to 125 ± 27 mL) following the 12 week PR programmes. This decrease in abdominal end expiratory volume following PR was thought to be attributable to

an increase in abdominal muscle activity, or a combination of prolonged expiration in association with increased abdominal contraction. In this research, a trend towards decreases in abdominal motion was also observed after PR. However, these results cannot be directly compared because of the different measurement systems that were used.

As discussed earlier, this trend in the direction of change appears to be counter-intuitive. It is generally believed that respiratory disease is associated with increased ribcage movement, with little abdominal activation, which has been predominantly attributed to diaphragm insufficiency (De Troyer et al. 1997; Cahalin et al. 2002; Ottenheijm et al. 2005). However, despite this common belief, there is a lack of data on regional chest contributions in patients with chronic respiratory diseases, and few studies comparing data before and after any interventions that have been associated with improvements in respiratory related symptoms. The lack of data means that there are no 'normalised' reference values against which to compare the results.

8.7.3.2 Speech breathing pattern variability before and after PR

The extremes of resting breathing variability (either too high or too low) have previously been associated with respiratory disease (Kuratomi et al. 1985; Brack et al. 2002). It was therefore hypothesised that speech breathing variability might alter in response to a PR programme. However, no changes were observed when examining speech breathing variability before and after PR during any of the breathing or speech tasks. Although there is no previous literature to compare these findings to, these observations are in line with the mean breathing and speech breathing pattern data, which also did not change from before to after PR. An intervention designed to improve chronic respiratory disease did not alter speech breathing pattern variability in this research.

8.7.3.3 Possible reasons for some of the negative findings

1. *Small sample size*

It is possible that statistically significant differences were not detected before and after PR because the sample size was insufficiently powered to detect a significant difference for any of the breathing parameters. Retrospective power calculations suggested that based on respiratory rate (during the conversational speech task), the power achieved in the current study was only 40%. Based on

the results obtained in the current research, table 61 presents the sample size required for a future before and after study based on 80% power to detect a statistically significant difference at the 0.05 alpha level for expiratory time, expiratory magnitude, respiratory rate and %RCExp:

Breathing parameter	Expected mean difference	SD of the mean difference	Sample size base on 80% power
Expiratory time (seconds)	0.5	±0.93	28
Expiratory magnitude (arbitrary units)	0.40	±0.69	24
Respiratory rate (breaths per minute)	1	±2.05	33
%RCExp	5	±19.90	195

Table 61 Sample size required for a future study based on the results from the current research

2. *The intensity and duration of the Pulmonary Rehabilitation programme*

It is possible that significant changes in breathlessness and physiology were not observed because the intensity and duration of the PR programme was insufficient to generate change. However, functional walking distance did improve significantly (although some of that increase may have been learning effect due to failure to repeat the test at baseline). While the optimal length of PR currently remains unclear (Spruit & Singh 2013; GOLD 2014), RCTs examining the effect of short term versus long term PR programmes have largely suggested that PR interventions with longer durations have a more favourable effect on patient centred end points, including breathlessness (Green et al. 2001; Berry et al. 2003; Verrill et al. 2005; Lacasse et al. 2007). Improvements in breathlessness and other patient centred outcomes have been documented when the duration of the PR intervention has lasted more than eight weeks, with participants attending three sessions per week (Lacasse et al. 2007; Spruit & Singh 2013).

Numerous trials have examined the impact of duration of PR programmes on outcomes (Troosters et al. 2000; Berry et al. 2003; Lacasse et al. 2007). Some of these trials have been subject to a systematic review (Beauchamp et al. 2011). Five RCTs were included and assessed as being of 'moderate' quality. Since a meta-analysis was not possible because of heterogeneity of the PR content and outcome measures, the results of the review were inconclusive. However, based on the individual findings of the RCTs, the longer programmes were found to be associated with greater patient benefits, with a minimum of eight weeks recommended to achieve substantial effects.

Clinically, the duration of PR is determined by the availability of staffing and financial resources, which is generally why the NHS cannot support the existence of 'longer' PR programmes. In this research, the PR programme lasted for a period of six weeks, with participants attending two supervised sessions per week. Since a six week programme is below the reported threshold for achieving 'substantial effect', it is possible that changes in breathing and speech breathing patterns were not observed because the duration of the PR programme was too short to achieve changes in these variables.

Other factors may also contribute to the efficacy of the duration of the PR programme, such as disease severity. In a previous meta-analysis which was designed to determine the efficacy of PR in patients with COPD, 20 RCTs (979 patients) were identified from MEDLINE, CINAHL and the Cochrane database (Salman et al. 2003). A meta-regression analysis was performed on the walking distance that was achieved during an ISWT in order to examine the association between this measure and PR programme characteristics (such as duration of the programme). No other patient outcomes were examined. In trials that included patients who were classified as having severe COPD, the rehabilitation groups performed significantly better when compared to the control when the duration of PR was more than six months. There were two studies (n = 68) where PR lasted less than three months which favoured the control group, whereas studies lasting more than six months favoured the treatment arm (n = 198). The severity of the disease (as defined by objective lung function tests) also appeared to influence the extent of the patient outcomes following PR. Studies that included patients with mild to moderate COPD performed better in the short and long term programmes. However, in patients with severe COPD, walking distance was found to be better when they participated in the longer

term programmes (more than six months). Although these findings were based on pooled data which was considered as being heterogeneous, they suggest that the optimal duration of PR could also be influenced by the severity of the disease. In this research, patients with COPD and bronchiectasis were classified as having 'severe' airway obstruction (mean FEV₁ %predicted = 48.38) based on the GOLD criteria (GOLD 2014). Therefore, it is possible that these patients may have required a training period lasting at least six months in order to observe significant changes in some parameters (Salman et al. 2003).

3. The content of the Pulmonary Rehabilitation programme

Although the content of PR has been described as being multidimensional, exercise training has been considered as the cornerstone of the intervention. In agreement with previous trials examining the efficacy of PR, significant improvements in exercise capacity were observed in the current investigation, which was possibly attributable to the dense exercise content of the PR programme. Education, medication optimisation and supervised breathing retraining techniques (which aim to 'normalise' breathing pattern, prolong expiration, and reduce respiratory rate and overall ventilation (Hill 2006; Lacasse et al. 2007; Ries et al. 2007) are also embedded into the core of the programme. However one of the challenges with comparing between programmes is that the content of PR has not yet been standardised and there is considerable variation between hospitals (Spruit & Singh 2013; GOLD 2014). While improvements in exercise capacity may influence breathing pattern, breathing retraining is the component of PR which is most likely to affect breathing and speech breathing patterns. The teaching of breathing re-training aims to modify ineffective breathing patterns which are a common feature of a number of chronic respiratory diseases (Casciari et al. 1981; Dechman & Wilson 2004). In this research, physiotherapy administered breathing retraining was taught during only one session in a group setting (lasting one hour) throughout the six week period. Patients were taught a combination of breathing control exercises, pursed lip breathing (PLB) and diaphragmatic control (DC). Breathing retraining for asthma, on the other hand, is usually taught on a one-to-one basis over several weeks (Thomas et al. 2003). In patients with COPD, breathing retraining is believed to improve breathing control, reduce dynamic hyperinflation and reduce respiratory rate. These mechanisms have been associated with improved gas exchange and increased tidal volumes (Mueller et al. 1970; Casciari et al.

1981; Breslin 1992). The optimal duration of breathing retraining required to have an effect in COPD is currently unclear (NICE 2010; Spruit & Singh 2013). In this research, it is possible that the duration and intensity of breathing retraining was not long enough for patients to learn and maintain modified breathing and speech breathing patterns.

4. Ceiling effect of some of the measures

The lack of detectable change between the baseline and post PR breathlessness score may have been because there was no room for improvement, as the level of self-perceived breathlessness was too low at baseline for any changes to occur. Breathlessness and breathing pattern can be seen to be closely related, as the symptom of breathlessness is directly related to specific parameters of breathing pattern, such as respiratory rate, timing components and lung volume (Muers 1993; Rao & Gray 2003). Episodes of increased breathlessness are characterised by having an increased respiratory rate, shorter respiratory timing components (such as inspiration and expiration time and breathing cycle time), and smaller lung volumes. Therefore, it is possible that differences in breathing and speech breathing patterns were not detected because they were related to the symptom of breathlessness, which was found to remain stable throughout the duration of PR in this research.

5. The influence of respiratory disease on breathing/speech breathing patterns is irreversible

It is possible that changes were not observed before and after PR because altered speech breathing patterns are irreversible, and do not 'change back', even when a respiratory disease improves. Although there is no previous literature to compare these findings to, one indication which suggests that alterations in speech breathing patterns might be irreversible is that objective measures of lung function (such as FEV₁) do not improve throughout the natural progression of COPD, even in response to a PR programme (Niedermaier et al. 1991). Even though pharmacological bronchodilators are shown to improve FEV₁ acutely, following an episode of bronchospasm, the long term effects are not equivalent. Therefore, it is possible that therapeutic interventions (such as PR)

can improve functional ability, and enable patients to cope with symptoms like breathlessness, without altering the underlying pathology.

8.7.4 Summary of section 8.7

Although functional exercise capacity significantly improved, no clinically or statistically significant changes in breathlessness or breathing parameters relating to respiratory timing, magnitudes or regional contributions of the ribcage and abdomen were detected following a six week PR programme for patients with COPD and bronchiectasis.

8.8 Limitations and technical issues

8.8.1 Evaluation of the semi-automatic algorithm

Earlier in this thesis (chapter six, section 6.1.7) it was discussed that breathing parameters relating to timings, volumes and the regional contributions of the rib cage and abdomen were extracted from the raw data files using a semi-automatic peak detection algorithm. In brief, breathing cycles were detected by the algorithm which identified local minima and maxima within the RIP signal (ie, the peaks and troughs), which signified the beginning and end of each inspiration phase. However, in circumstances where movement could influence the quality of the RIP signal that was recorded, introducing artefacts, the algorithm would occasionally incorrectly identify the start and end of the inspiration phase. The observation that RIP does not respond well to body movement is not an uncommon finding, as previous studies have also outlined the artefactual problems associated with recording breathing pattern using RIP during periods of movement, such as during exercise (Caretto et al. 1994; Clarenbach et al. 2005). In this research, movements were more commonly found to occur during the conversational speech task, as participants occasionally used hand gestures to aid their verbal communication, even though they were encouraged to remain still throughout the recordings.

In order to ensure that each inspiration phase was correctly identified by the peak detection algorithm, each speech breathing file required validation. This was performed in order to certify that each inspiration phase corresponded with

a period of silence in the speech signal, because speech is primarily driven by the expiratory phase (Hoit et al. 1989; Hoit et al. 1990; Winkworth et al. 1995). While the adjustment of speech breathing patterns was validated against the speech signal, this procedure could not be performed from data obtained during the quiet breathing task, as no speech was recorded. Instead, the beginning and end of each inspiration phase were validated by listening to the inhalation and exhalation (the flow of air in and out of the lungs) in the adjacent recording signal.

For each breathing and speech breathing file, a decision was made to either: keep, move, delete or add a marker so that the beginning and end of each inspiration phase was accurately verified. A record of how many times each of the 'adjustments' (move, add, delete) was applied to each data set has been provided in appendix 8.

It was consistently observed (throughout each data set: healthy adults, healthy older adults, adults with self-reported asthma and patients with chronic respiratory disease), that the quiet breathing task required fewer adjustments than the speech tasks. The total number of adjustments recorded during the quiet breathing task ranged from 17 to 59, in 20 healthy older adults and 15 patients with CRD (post PR) respectively. The quiet breathing task probably allowed participants to remain more still throughout the recordings, as no speech was involved.

In contrast, there was a distinct increase in the number of adjustments that was required for the speech tasks. For example, the total number of adjustments performed for all participants with chronic respiratory disease (post PR) was 121 (during the reading task), 107 (during the counting task) 105 (during the conversational speech task). This was roughly double the amount of adjustments that were performed for the quiet breathing task in the same cohort (n=59). As discussed, the most likely explanation is that participants were unable to remain completely still throughout the recordings because of the subconscious hand gestures, which caused artefacts in the RIP signal and therefore required more adjustments. Furthermore, the artefacts interfered with the RIP signal making it unclear where the exact start and end of each inspiration phase was. This was reflected by looking at the breakdown of what adjustments were applied to the data, as the decision to 'move' was consistently

associated with the greatest number of adjustments throughout all data sets and tasks.

Finally, another consistent observation relates to the data obtained from participants with chronic respiratory disease (before, during and after PR) which consistently required more adjustments than the healthy participants. It has been well established that patients with chronic respiratory disease demonstrate abnormal breathing mechanics, particularly due to impaired diaphragmatic control and the recruitment of accessory muscles (Cahalin et al. 2002; Frisk et al. 2014; GOLD 2014). Although the reason why patient data required more adjustments remains speculative, it is possible that artefacts were generated in the RIP signal because of abnormal accessory muscle activity during tidal breathing. However, despite these issues, the average number of the adjustments remained low. For example, the highest number of total adjustments was 126, which was recorded during the spontaneous speech task in patients with chronic respiratory disease (before PR). This equated to an average of 6 adjustments per participant in an average of 32 breathing cycles (over a two minute period) per participant.

In contrast, the data from adults with self-reported asthma required fewer adjustments during the data extraction phase, where the number of adjustments were found to be similar to those performed for healthy younger adults. However, it is not possible to draw any firm conclusions from the data acquired from adults with self-reported asthma, as asthma status was not clinically confirmed in this research.

In conclusion, the ability of the semi-automatic algorithm to identify breathing cycles through the detection of the local minima and maxima was influenced by the quality of the RIP signal and movement artefacts, which were thought to be caused by spontaneous bodily movements during the recordings. While movement artefacts were more commonly associated with the speech tasks, the actual number of adjustments that were required was found to be low. The advantage of using a semi-automatic algorithm was that the peaks and troughs (marking the beginning and end of inspiration) could initially be objectively identified by the algorithm, reducing some of the subjectivity associated with purely visual detection of breathing cycles used in previous studies (Loudon et al. 1988; Hoit et al. 1989; Lee et al. 1993). However, at present the process of

extracting speech breathing cycles is complex and time consuming. While these methods may be appropriate for use during laboratory based exploratory work, these methods would not be suitable for use in the clinical environment, because of the time required for post recording processing. If speech breathing pattern analysis is to become translated into the clinical setting in the future, simpler methods will be required to extract, analyse and report the data. In particular, there is a need to define the normative limits for each parameter. If the magnitude of the shortest breathing cycle could be defined (knowing how short is too short), the algorithm would be able to automatically reject more of the inappropriately detected peaks. This would require the recording of speech breathing patterns from a sample representing the wider population using standardised methods.

8.8.2 Technical limitations

All three studies in this investigation were subject to a number of technical limitations. Although the custom-made data acquisition box meant that data from the RIP system could be converted into digital form, the data acquisition box was subject to several technical failures during the data collection process. The main issues encountered included: a) loose connections between the microphone port and data acquisition box b) power supply disconnections and c) loosening of the abdominal and rib cage sockets. These were possibly encountered during the transportation of the equipment between the University of Southampton and St. Richard's Hospital, Chichester. Unpacking the equipment at the beginning and end of each data collection sessions may have also contributed to these complications. This meant that several opportunities to record data were missed. In the third study, the data could not be collected at any other time because data collection sessions were standardised according to the PR schedule within the hospital.

8.8.3 Indirect measurement of patient clinical data

In the third study, information relating to patient outcome data, including self-perceived breathlessness (obtained using the Modified Borg Scale) and functional walking distance (measured during the shuttle walk test), were obtained from patient notes. This may have been a potential limitation of the investigation because the researcher was not there to observe these

assessments, and it was not clear whether the respiratory physiotherapist adhered to published guidelines during these assessments. Furthermore, data relating to lung function were not obtained on the baseline assessment due to therapist time constraints, so it was recorded up to six weeks prior to the beginning of PR. It is therefore unclear whether the lung function data provided an accurate representation of the patients lung function at the start of PR.

8.8.4 Design

The purpose of the third study was to examine whether speech breathing patterns altered following a six week PR programme. Ideally, the study needed an 'inactive' control group so that comparisons could be made between the intervention (PR) versus an inactive control (patients not receiving the intervention), where the primary comparison would be between the two groups post intervention. In order to randomise patients into either arm of the trial, a 'waiting list control group' would usually be used. If patients were randomised to the control group, they would be asked to postpone their PR until their breathing/speech breathing patterns had been recorded three times over a six week period. They would then be able to begin their PR after this period. A waiting list control group would be more ethical to employ within a rolling PR programme, where patients can join the programme at any time point. In contrast, a cohort programme is structured so that the same patients complete one programme. While the benefits of a cohort programme relate to continuity, the waiting time between programmes are generally longer, as unlike rolling programmes, patients cannot join at any time point. Since the PR programme in the current study was based on a cohort model, it was felt that employing a waiting list control group would not be ethical, because of the delay in treatment. Furthermore, the time constraints associated with the PhD was also a barrier to employing a control group.

8.8.5 Sample size

Finally, a general limitation of all three studies relates to the small sample size recruited. In all three studies a convenience sample was sought on the basis that no previous reports have documented speech breathing characteristics in a heterogeneous sample, as earlier studies examined speech breathing patterns according to specific characteristics; sex (Hoit et al. 1989), age (Hoit & Hixon

1987; Hodge & Rochet 1989; Hoit et al. 1990) and lung disease (Loudon et al. 1988; Lee et al. 1993). None of the study samples were based on a power calculation; the absence of a power calculation could expose the comparative statistical analyses to type two errors (false negative).

8.9 Summary of chapter eight

The findings of this research have been discussed and contextualised in relation to the existing literature, and the limitations of the three studies. The final chapter in this thesis presents the conclusions of the research in relation to the research questions specified throughout chapter seven.

Chapter Nine

Conclusion

9.1 Introduction

The body of research in this thesis aimed to evaluate speech protocols for use when studying speech breathing patterns, and to characterise and compare speech breathing patterns between health and in chronic respiratory disease. Information gathered from this work was taken forward to explore the impact (if any) on speech breathing patterns in patients with COPD and bronchiectasis before and after an intervention targeting a sound evidence base for effectiveness (Pulmonary Rehabilitation) (Lacasse et al. 2007; NICE 2010; BTS 2013). If speech breathing parameters had been found to alter significantly in response to the PR programme, this would support the hypothesis that analysis of speech breathing patterns has potential as a respiratory monitoring tool, and/or as an outcome measure, for evaluating respiratory health following a therapeutic intervention of known effect.

9.2 Research Conclusions

The conclusions drawn from this body of research have been presented in relation to the initial research questions, which were specified throughout the results chapter (chapter seven).

- 1. Is the detection of breathing cycles using a semi-automatic algorithm feasible for extracting breathing and speech breathing parameters from the raw data files?**
 - a. This research has demonstrated the feasibility of using a semi-automatic algorithm for the detection of breathing cycles. The advantage of this method is that it reduces some of the subjectivity associated with former data extraction methods, which solely relied on visual or aural detection of breathing cycles. However, simpler automated methods for extracting/analysing speech breathing data will be required if speech breathing pattern analysis is to be translated into clinical practice in the future.

2. Do breathing and speech parameters remain stable throughout a four minute recording period in healthy adults during a quiet breathing, reading, describing and conversation task?

- a. This research has demonstrated the possibility of using shorter recording time periods for the assessment of speech breathing patterns, because all speech breathing parameters remained stable during both two minute and four minute recording periods during every task. Reducing the recording period of speech breathing patterns could improve the efficiency of research protocols, particularly for patients with CRD who experience speaking related breathlessness, while still providing meaningful data for clinical interpretation.

3. What is the optimal speech task(s) for use during speech breathing assessments?

- a. The describing task was found to have limited clinical utility during assessment of speech breathing patterns because of the fluency related difficulties experienced while performing the task. Due to these difficulties, the use of a describing task has not been recommended as a surrogate for spontaneous speech during future speech breathing assessments.
- b. When differentiating between healthy older adults and pooled patients with CRD (see conclusion/research question 8a), the conversational speech task highlighted the greatest number of differences between the two groups, and was comfortable for participants to perform. A conversational speech task is therefore recommended for use during future speech breathing assessments involving patients with respiratory disease.

4. Are breathing and speech breathing parameters significantly influenced by age or sex in healthy adults?

- a. The regional contributions of the ribcage and abdomen during quiet breathing and speech might be influenced by age, but not sex. Although these findings were not conclusive, future research should take age into consideration, particularly when interpreting findings and comparing between groups.

5. **Do healthy younger adults produce ‘task specific’ breathing and speech breathing patterns during a quiet breathing, reading, describing and conversation task?**
 - a. In healthy young adults speech breathing patterns were significantly influenced by the type of speech spoken. They were able to significantly differentiate between constrained (reading) and unconstrained speech (conversational speech and describing), as well as between speech and quiet breathing. The task specific nature of speech breathing behaviours should be taken into consideration when interpreting future speech breathing patterns in healthy cohorts.

6. **Do healthy older adults produce ‘task specific’ breathing and speech breathing patterns during a quiet breathing, reading, counting and conversational speech task?**
 - a. The distinction between constrained and unconstrained speech tasks became less obvious in healthy older adults. Further research is required to confirm these findings, as reducing the ability to produce task specific breathing patterns might represent another mechanism of change throughout the aging pathway.

7. **Do patients with chronic respiratory disease (COPD, bronchiectasis (CRD) and adults with self-reported asthma) produce ‘task specific’ speech breathing patterns?**
 - a. The distinction between the speech tasks was also less clear in adults with self-reported asthma. However, no firm conclusions can be drawn from these findings, as asthma status was not clinically confirmed.

 - b. There was no evidence to suggest that pooled patients with CRD produced task specific breathing patterns. If confirmed by future research, the inability to produce task specific breathing patterns might represent another mechanism to differentiate between health and chronic respiratory disease.

8. **Can speech breathing pattern analysis be used to differentiate between healthy older adults and pooled patients with CRD?**
 - a. Speech breathing patterns were significantly different between healthy older adults and pooled patients with CRD.

- 9. What breathing/speech task is the most useful for highlighting the differences between health and CRD?**
- a. In parallel to conclusion 3b, the greatest number of significant differences between healthy older adults and pooled patients with CRD were identified during spontaneous speech – conversation. A conversational speech task should be more useful for highlighting the differences between health and chronic respiratory disease in future speech breathing studies.
- 10. Can speech breathing pattern analysis significantly differentiate between CRDs (ie, between COPD and bronchiectasis)?**
- a. This research did not find any evidence to support previous claims that speech breathing patterns are disease specific. However, the insufficiently powered sample size meant that firm conclusions could not be drawn from these results.
- 11. Do breathing and speech breathing patterns in pooled patients with CRD alter following a six week PR programme?**
- a. Although functional exercise capacity was found to significantly improve following PR, no changes in breathlessness or speech breathing parameters were observed during any of the tasks. No firm conclusions can be drawn from this finding because of the uncontrolled nature of the study and the small sample may not be representative of the wider population. Larger controlled studies are needed to test the possibility that objective measurements of speech breathing patterns alter over time, or in response to clinical interventions with a sound evidence base for effectiveness.

Conclusion

The analysis of speech breathing patterns has shown some potential for future use as an objective respiratory monitoring tool, and/or as an outcome measure following clinical interventions. Speech breathing protocols have been optimised, supporting the use of shorter recording periods, and suggesting that a conversational speech task should be used when investigating any differences in speech breathing pattern between health and disease. However, before speech breathing pattern analysis can be recommended for future clinical use,

there are several areas which need further development. To be clinically useful, more simplified data extraction methods are needed to reduce the time required to extract, analyse and interpret the data. While this research has enhanced previous knowledge regarding the distinction between health and disease in terms of mean differences and task specificity, further work is still required to determine whether speech breathing patterns alter over time, either throughout the disease pathway, or following a clinical intervention of known effect (such as breathing retraining). The final chapter of this thesis will outline some of the possible areas for future research.

Chapter Ten

Future research

10.1 Introduction

This is the first time that speech breathing pattern analysis has been considered for its potential use in the field of respiratory monitoring. In line with the increase in respiratory related hospital admissions (Connolly et al. 2006), chapter two revealed the drawbacks associated with current respiratory monitoring techniques, and highlighted the need for newer methods that could quantify small changes in lung health earlier in the disease process, before overt respiratory symptoms develop. Although this research has supported the observation that that speech breathing patterns differ between health and chronic respiratory disease, it still remains unclear as to how these patterns alter over time, in response to disease progression, when respiratory symptoms deteriorate, or following a therapeutic intervention. A summary of the main areas for future research will now be considered.

10.1.1 Examination of the stability of speech breathing patterns over time within patients with chronic respiratory disease

If speech breathing pattern analysis is to translate into clinical practice in the future, further research is needed to determine the stability of speech breathing patterns over time. The stability of speech breathing patterns needs to be measured during consecutive hours, and days during stable periods of respiratory disease. While this research found that speech breathing patterns remained stable over a six week period in patients undertaking PR, only three measurements were taken over the six week period. Therefore, it is unclear how speech breathing patterns change (or remain stable) on a day to day basis. Determining the stability of speech breathing pattern is particularly important if this measure is to be considered as a respiratory monitoring tool. If speech breathing patterns are found to be too variable during consecutive days during stable periods of the disease, speech breathing pattern analysis would have limited clinical utility for respiratory monitoring.

10.1.2 Exploration of speech breathing patterns over a longer period of time

Research is required to pursue the possibility of detecting changes in speech breathing patterns over longer periods of time, which correlate with either an improvement or decline in patient clinical outcomes. Although this research has shown that speech breathing patterns are different between health and respiratory disease, it is not clear at what point these changes occur. Longitudinal studies are required to determine how speech breathing parameters relate to disease severity, and / or fluctuate with exacerbations. To determine this, research is needed to characterise speech breathing patterns in patients with chronic respiratory disease during different stages of the disease, to determine how, and if speech breathing patterns relate to objective measures of lung function throughout the disease process.

10.1.3 Responsiveness of speech breathing patterns to a therapeutic intervention

Ideally, a controlled design would be used to assess the effects of any intervention. In this research, speech breathing patterns were observed before and after a six week PR programme within patients with chronic respiratory disease. An intervention that might be expected to change breathing patterns and speech breathing patterns could be physiotherapy breathing retraining. Future research could therefore examine speech breathing patterns before and after a breathing retraining programme using a randomised controlled trial design, as well as incorporating patients with different chronic respiratory pathologies.

10.2 Implications for clinical practice

It is too soon to know if speech breathing patterns will be a useful tool for the remote monitoring of respiratory health. The concept is attractive, because samples of speech are readily available across any distance via telephones. Clinicians know that patients' ability to form full sentences becomes impaired when they are breathless, but it is not yet known how speech breathing patterns relate to any underlying pathology, or how they respond to specific interventions.

Appendices

Appendix 1 – Participant recruitment poster (Study one and two)

v2.0: Ethics No: Date: Nov 2010

UNIVERSITY OF Southampton
School of Health Sciences

Breathlessness can be a frightening and disabling symptom.

Would you like to help health care professionals improve the way they monitor patients with chronic lung conditions?



We need your help to determine whether we can monitor patients breathing patterns from their speech patterns.

If you would like to participate, you will attend a 'one off' recording session that will last 40mins. Your breathing and speech patterns will be recorded during 3 speech tasks by speaking into a microphone.

We would like to hear from you if...

- ✓ You are over the age of 18

For further information please contact

Sokhsaobh Jernay
Room 47, building 45
Faculty of Health Sciences
University of Southampton
Email: rt2y07@soton.ac.uk
Tel: 07958830304

Call or email Nancy on 07958830304 or n2y07@soton.ac.uk

Call or email Nancy on 07958830304 or n2y07@soton.ac.uk

Call or email Nancy on 07958830304 or n2y07@soton.ac.uk

Call or email Nancy on 07958830340 or n2y07@soton.ac.uk

Call or email Nancy on 07958830304 or n2y07@soton.ac.uk

Call or email Nancy on 07958830304 or n2y07@soton.ac.uk

Appendix 2 – Participant Information Sheet (PIS) (study two)

Participant Information Sheet (PIS)

Speech Breathing in Adults.

You are being invited to take part in a research study. Before you decide whether you would like to participate, it is essential that you understand the purpose of the research and what it will involve if you wish to take part. Please take time to read the following information and discuss it with others if you wish. It is important that you understand all of the information before you decide whether or not you would like to take part in the research. Please contact us if there is any more information that you require or if anything is unclear.

What is the purpose of this study?

Breathlessness is a common symptom experienced by many patients with chronic lung conditions. Research has shown that breathing patterns in these patients can be altered. It is difficult to monitor breathing patterns because it usually involves the use of mouth pieces or facemasks which can be restrictive, particularly for patients with respiratory conditions. We are experimenting with ways of monitoring breathing patterns from people's speech patterns. We would therefore like to record breathing and speech patterns from 40 people to test our theories.

Why have I been chosen?

You have been chosen because we would like to record breathing and speech patterns from a group of 40 adults.

Do I have to take part?

It is entirely your decision whether or not you decide to participate in this study. If you do part, you will be asked to sign a consent form. In addition, you are free to withdraw from the study at any point during the procedure without having to give a reason.

What will happen to me if I take part?

If you indicate that you would like to take part in this study, the researcher (Roxy Tehrani) will contact you to organise a convenient time and date to attend a breathing and speech pattern recording session at the University of Southampton. This will take approximately 40 minutes. When you arrive you will be given a chance to ask any questions. You will then need to fill in and sign a consent form. In order for the breathing apparatus to record your breathing patterns, two elastic belts with built in sensors will be attached around your upper chest and abdomen (tummy). The belts will need to be attached close to your skin in order to record your breathing patterns, therefore you will need to wear a vest or minimal undergarments on your top half to ensure that the sensors make close contact with your skin. If you wish, your outer garments (i.e. t-shirt) can then be replaced over the top of the belts to cover you up. As you breathe, signals from the belts are sent down some wires for recording. You will not feel anything while this is happening. We will ask you to sit quietly in a chair and complete a short

questionnaire about your age, sex and general health. We will then ask you to speak into a microphone during three different speaking tasks. These will involve reading a piece of text out loud, answering some questions about your daily routine and to describe a picture. Each speaking task will take 3-4 minutes. The belts will then be removed and you will be free to go.

What are the side effects of any treatment received when taking part in this study?

There are no known side effects from taking part in this study.

What are the possible disadvantages in taking part in this study?

There are no known disadvantages or risks from taking part in this study.

What are the possible benefits of taking part in this study?

There are no direct benefits from you taking part in this study. It is hoped that the information gained from this study may be used to monitor breathing patterns in patients with chronic lung disease. This could lead to improved understanding of breathing patterns by health professionals and patients, as well as improved management of patients with chronic lung disease.

Will my taking part in this study be kept confidential?

All information collected during the research process will remain confidential. Any data that is collected from you will have your name removed and will be allocated with an individual code so that you will not be able to be identified. The information will be stored on a password protected laptop which will be stored in a locked cupboard with in the university.

What will happen to the results of the research study?

The information recorded from breathing and speech patterns will be converted into figures for analysis. Some of the information may be used to develop future research ideas. The findings may also be written up in the form of reports or research articles and published at conferences or in academic journals. If this happens, you will not be identifiable.

Who has reviewed the study?

The study has been reviewed by the Ethics committee of the Faculty of Health Sciences. Ethics number: FoHS-ETHICS-2011-038

What to do if you want to complain.

If you have a concern or a complaint about this study you should contact Susan Rogers, Head of Research & Enterprise Services, at the Faculty of Health Sciences (Address: University of Southampton, Building 67, Highfield, Southampton, SO17 1BJ ; Tel: +44 (0)23 8059 7942; Email: S.J.S.Rogers@soton.ac.uk). If you remain unhappy and wish to complain formally Susan Rogers can provide you with details of the University of Southampton Complaints Procedure.

Thank you for taking the time to read this Information Sheet

If you would like any further information please contact:

Researcher
Rokhsaneh Tehrani

Supervisor
Anne Bruton PhD MA MCSP

Appendix 3 – Retrospective power calculations

Retrospective power calculations based on 80% power to detect a statistically significant difference at the 0.05 alpha level during the conversational speech task for expiration time, expiration magnitude, respiratory rate and %RCExp

Healthy young adults *versus* healthy old adults: sample size required for a future study (independent sample t test):

Breathing parameter	Group 1 mean (healthy young)	Group 2 mean (healthy old)	SD of the mean difference (during conversational speech)	Sample size based on 80% power
Expiratory time (seconds)	4.24	4.70	±1.49	322(166 per group)
Expiratory magnitude (arbitrary units)	1.96	1.50	±1.28	246 (123per group)
Respiratory rate (breath per minute)	12.11	11.70	±3.78	2672 (1336 per group)
%RCExp	64.82	83.38	±15.08	24 (12 per group)

COPD *versus* bronchiectasis: Sample size required for a future study (independent sample t test):

Breathing parameter	Group 1 mean (COPD)	Group 2 mean (bronchiectasis)	SD of the mean difference (during conversational speech)	Sample size based on 80% power
Expiratory time (seconds)	3.75	3.56	±0.96	804 (402 per group)
Expiratory magnitude (arbitrary units)	1.60	1.28	±0.76	180 (90 per group)
Respiratory rate (Breaths per minute)	14.35	14.62	±2.63	2982 (1491 per group)
%RCExp	62.61	53.02	±17.54	108 (54 per group)

Healthy young *versus* adults with self-reported asthma: Sample size required for a future study (independent sample t test):

Breathing parameter	Group 1 mean (healthy young)	Group 2 mean (self-reported asthma)	SD of the mean difference (during conversational speech)	Sample size based on 80% power
Expiratory time (seconds)	4.24	3.84	±1.57	486 (243 per group)
Expiratory magnitude (arbitrary units)	1.96	2.00	±1.41	372 (186 per group)
Respiratory rate (Breaths per minute)	12.11	14.21	±3.51	90 (45 per group)
%RCExp	64.82	64.39	±13.35	392 (196 per group)

Healthy older adults *versus* pooled patients with COPD: Sample size required for a future study (independent sample t tests):

Breathing parameter	Group1 mean (healthy older adults)	Group 2 mean (pooled patients with CRD)	SD of the mean difference (during conversational speech)	Sample size based on 80% power
Expiratory time (seconds)	4.70	3.68	±1.30	54 (27 per group)
Expiratory magnitude (arbitrary units)	1.50	1.87	±0.78	142 (71 per group)
Respiratory rate (Breaths per minute)	11.70	14.43	±3.68	60 (30 per group)
%RCExp	83.38	59.58	±15.67	16 (8 per group)

Appendix 6 – An *extract* from the reading task used in the first and second study

Reading Material for Participants

When we got to the strange house it began to snow in quite a different way. A mass of tired old clouds opened and flung snow at us, all of a sudden and just anyhow. They weren't ordinary snowflakes – they fell straight down in large sticky lumps, they clung to each other and sank quickly and they weren't white, but grey. The whole world was as heavy as lead. Mummy carried in the suitcases and stamped her feet on the doormat and talked the whole time because she thought the whole thing was such fun and that everything was different. But I said nothing because I didn't like this strange house. I stood in the window and watched the snow falling, and it was all wrong. It wasn't the same as in town. There it blows black and white over the roof or falls gently as if from heaven, and forms beautiful arches over the sitting-room window. The landscape looked dangerous too. It was bare and open and swallowed up the snow, and the trees stood in black rows that ended in nothing. At the edge of the world there was a narrow fringe of forest. Everything was wrong. It should be winter in town and summer in the country. Everything was topsy-turvy. The house was big and empty, and there were too many rooms.

Appendix 7 – An example of the describing material used during the ‘describing’ task (study one)



Appendix 8 - Evaluation of the semi-automatic algorithm used for extrapolating breathing parameters from the raw data files.

The following tables provide a breakdown of the number of times each raw data file had to be 'adjusted' during the data extraction process by implementing the 'rules' that were outlined in chapter 6 (**move, delete, add**). The following tables will now outline the number of adjustments for each participant according to the following data sets, where there were 530 data sets that were analysed in total;

- Healthy young adults
 - Quiet breathing
 - Reading
 - Describing
 - Conversational speech
- Adults with self-reported asthma
 - Quiet breathing
 - Reading
 - Describing
 - Conversational speech
- Healthy older adults
 - Quiet breathing
 - Reading
 - Counting
 - Conversational speech
- Patients with chronic respiratory disease Before PR (COPD and bronchiectasis)
 - Quiet breathing
 - Reading
 - Counting
 - Conversational speech
- Patients with chronic respiratory disease during PR (COPD and bronchiectasis)
 - Quiet breathing
 - Reading
 - Counting
 - Conversational speech
- Patients with chronic respiratory disease after PR (COPD and bronchiectasis)
 - Quiet breathing
 - Reading
 - Counting
 - Conversational speech.

Table 1 Number of adjustments: **Healthy young adults (n=29)** during quiet breathing, reading, describing and spontaneous speech.

ID	Quiet breathing task				Reading task				Describing task				Spontaneous speech task			
	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total
001	0	0	0	0	2	2	3	7	3	1	4	8	2	2	4	8
002	0	0	2	2	3	0	0	3	4	2	2	8	2	3	0	5
003	1	1	0	1	2	0	3	5	3	1	3	7	1	0	3	4
004	0	0	0	0	2	0	3	5	4	3	3	10	3	0	2	5
005	0	0	0	0	0	0	4	4	3	2	4	9	2	3	1	6
006	0	0	0	0	0	0	1	1	1	1	7	9	1	0	1	2
007	0	0	0	0	3	1	1	5	1	2	6	9	2	0	0	2
008	0	0	2	2	0	0	2	2	1	1	1	3	1	0	0	1
009	0	0	2	0	2	0	0	2	0	3	1	4	0	2	1	3
010	0	0	0	0	3	0	0	3	3	0	2	5	0	0	0	0
011	0	0	0	0	0	0	4	4	0	1	0	1	1	3	2	6
012	0	0	0	0	0	0	0	0	3	0	6	9	1	0	2	3
013	1	1	0	2	2	0	1	3	3	2	0	5	1	0	1	2
014	0	0	0	0	0	0	0	0	0	1	2	3	1	1	0	2
015	0	0	0	0	2	0	1	3	1	1	5	7	0	0	1	1
016	0	0	0	0	0	0	0	0	0	1	2	3	0	0	0	0
017	0	0	0	0	3	0	1	4	1	3	7	11	0	0	1	1
018	0	0	2	2	0	0	3	3	1	2	2	5	0	0	1	1
019	0	0	0	0	0	0	0	0	0	3	0	3	1	1	1	3
020	2	2	0	2	0	0	1	1	0	0	1	1	2	0	2	4
021	0	0	0	0	2	0	0	2	0	0	1	1	1	0	0	4
022	0	0	2	2	3	0	1	4	1	1	0	2	0	0	0	1
023	0	0	3	3	0	0	3	3	0	0	0	0	0	1	1	2
024	0	0	0	0	2	0	1	3	3	2	2	7	2	0	1	3
025	1	1	2	3	3	0	3	6	0	1	1	2	1	0	1	2
026	0	0	0	0	0	0	0	0	1	0	0	1	2	0	0	2
027	0	0	4	4	2	1	1	4	0	1	0	1	2	1	0	3
028	0	0	3	3	0	0	0	0	0	2	3	5	1	0	1	2
029	0	0	2	2	2	0	3	5	0	0	0	0	0	0	1	1
Total	5	5	24	32	38	4	40	82	37	37	65	139	30	17	28	79

Table 2 Number of adjustments: **Adults with self-reported asthma** (n=11) during quiet breathing, reading, describing and spontaneous speech

ID	Quiet breathing task				Reading task				Describing task				Spontaneous speech task			
	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total
001	0	1	0	0	1	1	1	3	3	0	2	5	1	1	3	4
002	0	0	1	1	2	0	0	2	1	0	5	6	3	2	3	8
003	0	0	0	0	2	2	0	4	1	2	2	5	2	0	3	5
004	0	0	1	1	0	0	1	1	1	3	1	4	0	0	1	1
005	0	0	1	1	0	0	3	3	2	2	1	5	0	0	1	1
006	0	0	0	0	1	0	0	1	2	2	2	6	4	0	1	5
007	0	0	2	2	1	0	3	4	3	1	4	8	2	0	2	4
008	0	0	2	2	3	0	1	4	3	1	1	5	0	0	2	2
009	0	0	1	1	0	0	2	2	0	3	3	6	0	0	1	1
010	0	1	0	1	1	0	3	4	4	1	2	7	0	0	2	2
011	0	0	3	3	0	0	0	4	1	1	1	3	2	4	2	8
Total	0	2	8	32	11	3	14	32	21	16	24	60	14	7	21	42

Table 3 Number of adjustments: **Healthy older adults (n=20)** during quiet breathing, reading, counting and spontaneous speech

ID	Quiet breathing task				Reading task				Counting task				Spontaneous speech task			
	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total
HO1	0	0	0	0	2	0	1	3	1	1	1	3	2	1	2	5
HO2	0	0	1	1	0	0	2	2	3	2	3	8	1	0	2	3
HO3	0	0	1	1	2	0	1	2	2	0	2	4	0	0	1	1
HO4	0	0	2	2	0	0	1	1	1	1	3	5	1	0	1	2
HO5	1	0	0	1	2	0	2	4	2	1	2	5	1	2	1	4
HO6	0	0	2	2	2	1	3	6	1	0	2	3	0	0	2	2
HO7	0	0	0	0	0	0	3	3	1	0	1	2	1	0	1	2
HO8	0	1	1	1	0	0	1	1	0	0	1	1	0	0	2	2
HO9	0	0	0	0	0	0	3	3	3	0	2	5	1	1	1	3
HO10	0	0	2	2	1	0	1	2	0	0	0	0	0	2	2	4
HO11	0	0	0	0	0	0	1	1	2	0	0	2	0	0	2	2
HO12	0	0	1	1	2	0	1	3	1	0	2	3	2	0	1	3
HO13	0	0	0	0	0	0	1	1	0	0	3	3	2	0	3	5
HO14	0	0	1	1	1	0	1	2	2	1	3	5	1	0	1	2
HO15	0	1	0	1	0	0	1	1	1	0	0	1	0	1	1	2
HO16	0	0	0	0	0	1	1	2	0	0	1	1	0	1	1	2
HO17	0	0	1	1	1	0	2	3	1	0	3	4	0	0	2	2
HO18	1	0	0	1	0	1	2	3	0	0	2	2	2	0	1	3
HO19	0	0	1	1	1	0	2	3	1	0	0	1	0	0	2	2
HO20	0	0	1	1	0	0	1	1	2	1	3	6	1	1	3	5
Total	2	2	14	17	14	3	31	47	24	7	34	64	15	9	32	56

-- Missing data

Table 4 Number of adjustments: **Patients with chronic respiratory disease Before PR (n=20)**- during quiet breathing, reading, counting and spontaneous speech

ID	Quiet breathing task				Reading task				Counting task				Spontaneous speech task			
	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total
PR1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PR2	-	-	-	-	1	1	1	3	1	0	4	5	1	1	2	4
PR3	-	-	-	-	2	0	1	3	0	1	1	2	0	2	2	4
PR4	-	-	-	-	1	1	3	4	1	0	1	2	1	2	2	5
PR5	-	-	-	-	2	2	3	7	0	1	5	6	1	0	4	5
PR6	1	1	1	3	1	0	4	5	1	0	4	5	1	0	3	4
PR7	3	1	1	5	1	0	1	2	1	0	6	7	3	0	5	8
PR8	1	1	1	3	1	0	1	2	1	1	3	5	2	1	2	5
PR9	1	1	3	5	2	1	1	4	1	0	1	2	1	1	6	8
PR10	1	1	2	4	3	1	4	8	2	0	7	9	2	1	3	6
PR11	2	0	3	5	1	1	5	7	1	0	4	5	1	0	6	7
PR12	0	0	1	1	1	0	3	4	1	0	3	4	1	1	4	6
PR13	1	1	2	4	4	0	3	7	2	1	3	6	1	1	5	7
PR14	1	0	2	3	1	0	5	6	2	0	6	8	2	3	3	8
PR15	0	2	1	3	2	1	3	6	2	3	3	8	3	3	3	9
PR16	1	0	1	2	1	1	4	6	2	1	6	9	1	1	1	3
PR17	2	0	1	3	4	0	1	5	2	1	1	4	1	3	6	10
PR18	0	1	2	3	1	0	2	3	1	1	1	3	1	1	7	9
PR19	2	1	1	4	1	0	2	3	4	2	3	9	3	3	2	8
PR20	1	1	2	4	1	1	6	8	2	2	3	7	2	2	6	10
Total	17	11	24	52	31	10	53	94	27	14	65	105	28	26	72	126

-- Missing data

Table 5 Number of adjustments: **Patients with chronic respiratory disease during PR (n=20)**- Quiet breathing, reading, counting and spontaneous speech

ID	Quiet breathing task				Reading task				Counting task				Spontaneous speech task			
	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total
PR1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PR2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PR3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PR4	-	-	-	-	-	-	--	-	-	-	--	-	-	-	--	-
PR5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PR6	-	-	-	-	1	2	1	4	3	0	5	8	3	1	2	6
PR7	1	1	2	4	0	1	1	2	1	2	2	5	1	2	4	7
PR8	0	1	1	2	1	1	1	3	1	0	4	5	1	3	5	9
PR9	1	0	2	3	0	0	2	2	1	2	3	6	2	1	2	5
PR10	1	1	1	3	1	1	4	6	3	2	2	7	2	0	4	6
PR11	0	1	2	3	0	2	5	7	2	2	3	7	2	2	2	6
PR12	3	0	1	4	2	1	5	8	1	2	2	5	3	2	3	8
PR13	1	0	3	4	3	1	5	9	0	1	5	6	2	2	6	10
PR14	2	0	1	3	0	1	6	7	2	0	6	8	1	1	2	4
PR15	1	3	1	5	2	1	7	10	2	1	7	10	3	1	1	4
PR16	2	0	2	4	4	3	6	13	3	1	6	10	0	0	6	6
PR17	2	3	1	6	3	1	3	7	4	3	4	11	3	2	1	6
PR18	0	1	1	2	1	2	2	5	2	1	5	8	2	3	6	11
PR19	2	0	3	5	2	3	3	8	2	0	4	6	3	1	7	11
PR20	1	1	1	3	4	2	6	12	2	1	7	10	1	1	2	4
Total	17	12	32	51	24	22	57	103	29	18	65	112	29	22	53	103

-- Missing data

Table 6 Number of adjustments: **Patients with chronic respiratory disease after PR (n=20)**- Quiet breathing, reading, counting and spontaneous speech

ID	Quiet breathing task				Reading task				Counting task				Spontaneous speech task			
	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total	Delete	Add	Move	Total
PR1	-	-	-	-	1	2	4	7	1	1	2	4	0	2	3	5
PR2	-	-	-	-	2	2	3	7	0	2	2	4	2	0	7	9
PR3	-	-	-	-	1	3	2	6	1	0	0	1	0	2	5	7
PR4	-	-	--	-	1	1	4	6	1	1	3	5	0	1	4	5
PR5	-	-	-	-	1	2	2	5	1	0	4	5	1	2	3	6
PR6	1	1	3	4	1	1	2	4	3	2	1	6	2	2	3	7
PR7	2	0	0	2	1	0	3	4	2	1	4	7	1	2	1	4
PR8	0	2	2	4	2	1	1	4	4	3	2	9	2	0	3	5
PR9	1	3	1	4	1	1	2	4	2	1	3	6	1	0	5	6
PR10	3	1	1	5	2	2	3	7	2	0	2	4	1	1	3	5
PR11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PR12	1	2	4	7	1	2	3	6	1	4	1	6	2	0	5	7
PR13	0	1	1	2	2	3	5	10	2	0	0	2	1	0	6	7
PR14	1	2	5	8	4	4	2	10	1	0	3	4	2	0	2	4
PR15	1	3	0	4	1	1	3	5	1	4	2	7	3	1	2	6
PR16	0	2	2	4	2	2	4	8	4	2	5	11	2	2	1	5
PR17	0	3	1	4	1	2	6	9	2	1	4	7	3	1	2	6
PR18	1	0	3	4	0	1	2	3	3	1	5	9	0	1	1	2
PR19	2	1	1	3	1	3	2	6	2	0	2	4	1	3	2	6
PR20	2	1	2	4	1	2	7	10	1	1	4	6	0	0	3	3
Total	15	22	26	59	26	35	60	121	34	24	49	107	24	20	61	105

-- Missing data

Appendix 9 – Faculty of Health Science ethical approval letter (study one and two)

UNIVERSITY OF
Southampton

EO4/Aug 2010/ v1.1

Rokhsaneh Tehrani
Faculty of Health Sciences
University of Southampton

20 February 2011

Dear Roxy

Ethics Submission No: FoHS-ETHICS-2011-038
Title: Speech breathing in adults

I am pleased to confirm full approval for your study has now been given. The approval has been granted by the Faculty of Health Sciences Ethics Committee.

You are required to complete a University Insurance and Research Governance Application Form (IRGA) in order to receive insurance clearance before you begin data collection. The blank form can be found at <http://www.soton.ac.uk/corporateservices/rop/reaprois/whatdops.html>

You need to submit the following documentation in a plastic wallet to Dr Martina Prude in the Research Governance Office (RGO, University of Southampton, Highfield Campus, Bldg. 37, Southampton SO17 1BJ):

- Completed IRGA Research Governance form
- Copy of your research protocol/School Ethics Form (final and approved version)
- Copy of participant information sheet
- Copy of SoHS Risk Assessment form, signed
- Copy of your information sheet and consent form
- Copy of this SoHS Ethical approval letter

Continued overleaf

Your project will be registered at the RCO, and then automatically transferred to the Finance Department for insurance cover. You can not begin recruiting until you have received a letter stating that you have received insurance clearance.

Please note that you have ethics approval only for the project described in your submission. If you want to change any aspect of your project (e.g. recruitment or data collection) you must request permission from the Ethics Committee and RCO (students should discuss changes with their supervisor before submitting the request to the Ethics Committee).

Yours sincerely

Dr Maggie Donovan-Hall
Vice Chair, FoHS Ethics Committee

t: +44 (0)23 8059 8880
e: mh699@soton.ac.uk
f: +44 (0)23 8059 4792

Faculty of Health Science ethics approval letter (Study 2)

Submission Number: 12246

Submission Name: Speech breathing in adults

This email is to let you know your submission was approved by the Ethics Committee.

You can begin your research unless you are still awaiting specific Health and Safety approval (e.g. for a Genetic or Biological Materials Risk Assessment)

Comments

1. Thank you for your request for ethical approval for this study. Given it has previously received ethical approval in its current form, and that you require to collect further data using the same application, I am happy to approve it, subject to the approval of my co-reviewer

[Click here to view your submission](#)

ERGO : Ethics and Research Governance Online
<http://www.ergo.soton.ac.uk>

DO NOT REPLY TO THIS EMAIL

Appendix 10 – Faculty of Health Science indemnity insurance confirmation letter (study one and two)



Miss Rokhsanch Tehrany
School of Health Sciences
University of Southampton
University Road
Highfield
Southampton
SO17 1BJ

RGO Ref: 7882

28 February 2011

Dear Miss Tehrany

Project Title Speech Breathing in Adults

This is to confirm the University of Southampton is prepared to act as Research Sponsor for this study, and the work detailed in the protocol/study outline will be covered by the University of Southampton Insurance programme.

As the sponsor's representative for the University this office is tasked with:

1. Ensuring the researcher has obtained the necessary approvals for the study
2. Monitoring the conduct of the study
3. Registering and resolving any complaints arising from the study

As the researcher you are responsible for the conduct of the study and you are expected to:

1. Ensure the study is conducted as described in the protocol/study outline approved by this office
2. Advise this office of any change to the protocol, methodology, study documents, research team, participant numbers or start/end date of the study
3. Report to this office as soon as possible any concern, complaint or adverse event arising from the study

Failure to do any of the above may invalidate the insurance agreement and/or affect sponsorship of your study i.e. suspension or even withdrawal.

On receipt of this letter you may commence your research but please be aware other approvals may be required by the host organisation if your research takes place outside the University. It is your responsibility to check with the host organisation and obtain the appropriate approvals before recruitment is underway in that location.

May I take this opportunity to wish you every success for your research.

Yours sincerely

Dr Martina Prude
Head of Research Governance

Indemnity insurance for study two:



To Whom It May Concern

Our ref: SP/IND

23 July, 2014

Zurich Municipal Customer: The University of Southampton and all its Subsidiaries

This is to confirm that The University of Southampton and all its Subsidiaries have in force with this Company until the policy expiry on 31 July 2015 Insurance incorporating the following essential features:

Policy Number: NHE-11CA11-0013

Limit of Indemnity:

Public Liability:	£ 50,000,000	any one event for all claims in the aggregate during any one period of insurance
Products Liability:	£ 50,000,000	any one event inclusive of costs
Pollution:		
Employers' Liability:	£ 50,000,000	

Excess:

Public Liability/Products Liability/Pollution:	Nil any one event
Employers' Liability:	Nil any one claim

Indemnity to Principals:

Covers include a standard Indemnity to Principals Clause in respect of contractual obligations.

Full Policy:

The policy documents should be referred to for details of full cover.

Yours faithfully

Underwriting services
Zurich Municipal
Farnborough

Zurich Municipal
Zurich House
2 Gladstone Way
Farnborough
Hampshire
GU14 6GB

Telephone 0870 2418050
t Phone: 01252 387927
telex Fax: 01252 375893
it.napier@uk.zurich.com

Communications will be monitored
by us to protect our service and
city and regulatory purposes

Zurich is a trading name of
Zurich Insurance Group Ltd

Our company is incorporated in
Ireland. Registration No. 13486
Our Zurich House, Ballsbridge
Park, Dublin 4, Ireland

Our company is authorised and
regulated in England and Wales
Registration No. 807985
Our Office: The Zurich Centre,
Parkway, Whiteley, Fareham,
Hampshire PO15 7JZ

Our company is authorised and
regulated in the Central Bank of Ireland
It is also authorised and regulated by the
FCA Authority. Details about
our authorisation and regulation by the Financial
Conduct Authority are available from us on
request

Appendix 11 – Participant invitation letter (study three)

Date: August 2nd 2012

Dear Patient,

I would like to invite you to take part in a research study which aims to examine breathing patterns before and after attending a 6 week Pulmonary Rehabilitation (PR) program. We hope to involve up to 40 patients who have been enrolled onto a PR program at St. Richard's Hospital, Chichester. You are being invited because your nurse/physiotherapist has recommended that you take part in a PR program.

I have enclosed a copy of the Participant Information Sheet (PIS) that will provide you with more information about the study and procedure if you choose to take part. Briefly, if you would like to take part, you will be invited to attend 3 separate recording sessions that will take place on the same day as the first, sixth and last PR session, which will be on a Tuesday or Thursday. During these sessions we would like to record your breathing patterns during different speech tasks, including reading, counting conversation, where each session will last approximately 20 minutes.

If you are interested in taking part, or would like further information, I would be grateful if you could **complete the enclosed reply slip and post using the pre-paid envelope provided**. I will contact you as soon as I receive the reply-slip on the contact details that you provide. Alternatively, **you can contact the researcher, Roxy Tehrany, directly on xxxxxx for further information**.

Whether you decide to take part or not will not affect your future treatment.

Yours sincerely,

Roxy Tehrany, MSc, BSc, MCSP

PhD Student and Physiotherapist
Postgraduate office,
Faculty of health sciences
University of Southampton,
Southampton
SO17 1BJ
Direct tel: xxxxxx
email: xxxxxxxx

Appendix 12 – Participant Information Sheet (Study three)

Participant Information Sheet (PIS)

Breathing patterns before and after attending a Pulmonary Rehabilitation programme.

You are being invited to take part in a research study. Before you decide whether you would like to participate, it is essential that you understand the purpose of the research and what it will involve if you wish to take part. Please take time to read the following information and discuss it with others if you wish. It is important that you understand all of the information before you decide whether or not you would like to take part in the research. Please contact us if there is any more information that you require or if anything is unclear.

What is the purpose of this study?

People with breathing problems often find they get breathless when talking. We would like to record your breathing pattern before, during after attending a 6 week Pulmonary Rehabilitation (PR) programme to see if there are any changes.

Why have I been chosen?

You have been chosen because we would like to record breathing and speech patterns from a group of 40 patients before, during after attending a 6 week PR programme.

Do I have to take part?

It is entirely your decision whether or not you decide to participate in this study. If you do decide to take part, you will be asked to sign a consent form. In addition, you are free to withdraw from the study at any point during the procedure without having to give a reason. This will not affect your PR classes.

What will happen to me if I take part?

If you indicate that you would like to take part in this study, you will be invited to attend 3 separate recording sessions that will take place on the same day as your first, sixth and last PR session at St. Richard's Hospital in Chichester, where each recording session will last approximately 20 minutes. The researcher, Roxy Tehrani, will contact you and advise you on the times and dates for each recording session once the dates of your PR course has been confirmed. When you arrive you will be given a chance to ask any questions and will then be asked to fill in and sign a consent form and questionnaire about your age, sex and general health. You will be asked to remove the clothing from your upper body, or to wear minimal undergarments, so that the breathing apparatus can be applied close to your skin. This consists of two elastic belts with built in sensors which go around your upper chest and abdomen (tummy area). If you wish, your outer garments can then be replaced over the top of the belts. As you breathe, signals from the belts are sent down some wires for recording. You will not feel anything while this is happening. We will then ask you to speak into a microphone during three different speaking tasks. These will

include; reading a piece of text out loud, answering some questions about your daily routine and counting. Each speech task will last 2 minutes. For the reading task, you may wear your reading glasses if needed. After that the belts will be removed and you will be free to go.

What are the side effects of any treatment received when taking part in this study?

There are no known side effects to taking part in this study.

What are the possible disadvantages in taking part in this study?

There are no known serious disadvantages or risks in taking part in this study.

What are the possible benefits of taking part in this study?

There are no direct benefits of you taking part in this study. It is hoped that the information gained from this study may be used to monitor breathing patterns in patients with lung problems. This could lead to improved understanding of breathing patterns by health professionals and patients and improved management of patients with lung disease.

Will my taking part in this study be kept confidential?

All information collected during the research process will remain confidential. Any data that is collected from you will have your name removed and will be allocated with an individual code so that you will not be able to be identified. The information will be stored on a password protected laptop that will be stored in a locked cupboard with in the university.

What will happen to the results of the research study?

The information recorded from breathing and speech patterns will be converted into figures for analysis. Some of the information may be used to develop future research ideas. The findings may also be written up in the form of reports or research articles and published at conferences or in academic journals. If this happens, you will not be identifiable.

Who has reviewed the study?

The study has been reviewed by the NHS Ethics committee

What to do if you want to complain.

If you have a concern or a complaint about this study you should contact Susan Rogers, Head of Research & Enterprise Services, at the Faculty of Health Sciences (Address: University of Southampton, Building 67, Highfield, Southampton, SO17 1BJ ; Tel: +44 (0)23 8059 7942; Email: S.J.S.Rogers@soton.ac.uk). If you remain unhappy and wish to complain formally Susan Rogers can provide you with details of the University of Southampton Complaints Procedure.

Thank you for taking the time to read this Information Sheet

If you would like any further information please contact:

Researcher

Roxy Tehrani MSc MCSP

Supervisor

Anne Bruton PhD MA MCSP

Appendix 13 – Participant reply form (Study three)

Reply slip.

Please fill out this reply-slip and post using the pre-paid envelope if you are interested in taking part in the study, or would like further information. The researcher will then contact you on the telephone number that you provide. Alternatively, you can contact the researcher directly on xxxxxxxx for further information.

Name:.....
.....

Telephone No.:

Please indicate a convenient time and date for the researcher to contact you:.....

Thank you.

Roxy Tehrany

Appendix 14 – Participant confirmation letter (Study three)

Date: xxx

Ethics committee number: xxxx

Dear Mr/Miss/Mrs xxx,

RE: Breathing patterns before and after attending Pulmonary Rehabilitation (PR).

Following our earlier telephone conversation on xxx, I am writing to confirm your place on the above study. As discussed, you are invited to attend **3 recording sessions that will take place on the same day as your first, sixth and last PR session**, which will be on a Tuesday or Thursday and will last 20 minutes each. The recording sessions will take place before you attend your PR class.

Once the dates of your PR sessions have been confirmed, I will send you a letter detailing the exact dates and times for each recording session.

In the meantime, if you have any questions regarding the study please do not hesitate to contact me on the contact details provided below.

Yours sincerely,

Roxy Tehrany, MSc, BSc, MCSP

PhD Student and Physiotherapist
Postgraduate office,
Faculty of health sciences
University of Southampton,
Southampton
SO17 1BJ
Direct tel: xxxxx
email: xxxxxx

Appendix 15 – Final study confirmation letter (study three)

Date: xxx

Ethics committee number: xxxx

Dear Mr/Miss/Mrs xxx,

RE: Research Study – confirmation of times/dates.

Following my previous letter on xxx, I am writing to confirm the times and dates of each recording session for the ‘breathing pattern’ study. As discussed, each recording session will take place on the same day as your first, sixth and last PR assessment, which will be on a Tuesday or Thursday. The times/dates for each recording session are as follows:

	Date:	Time:	Place:	Duration:
Recording session 1 -	xxxx	xxxx	xxxx	20mins aprox.
Recording session 2 -	xxxx	xxxx	xxxx	20mins aprox.
Recording session 3 -	xxxx	xxxx	xxxx	20mins aprox.

Each recording session will be the same where your breathing patterns will be recorded during 3 different speech tasks including, reading, counting and conversation. Please be aware that since the recording sessions will take place before your PR session session, I would therefore be grateful if you could arrange parking or transportation for this additional time that you will be here for.

I will look forward to meeting you on xxx

If you have any further questions or would like to withdraw from the study, **Please do not hesitate to contact me on xxxxxxxx**

Yours sincerely,

Roxy Tehrany, MSc, BSc, MCS

PhD Student and Physiotherapist

Postgraduate office, University of Southampton

Appendix 16 – Modified Borg Scale

The Modified Borg Scale

Please circle the number that best describes the level of breathlessness that you may be experiencing:

0	Nothing at all
0.5	Very, very slight shortness of breath
1	Very mild shortness of breath
2	Mild shortness of breath
3	Moderate shortness of breath or breathing difficulty
4	Somewhat severe
5	Strong or hard breathing
6	-
7	Severe shortness of breath or very hard breathing
8	-
9	Extremely severe
10	Shortness of breath so severe you need to stop

Appendix 17 – Faculty of Health Science indemnity insurance confirmation and NHS ethics approval letters



Miss Roxy Tehrany
School of Health Sciences
University of Southampton
University Road
Highfield
Southampton
SO17 1BJ

RGO REF - 8553
School Ethics Ref - 1267 -
ERGO

25 April 2012

Dear Miss Tehrany

Professional Indemnity and Clinical Trials Insurance

Project Title Speech Breathing Pattern Analysis before and after a Pulmonary Rehabilitation Programme

Participant Type:	No Of Participants:	Participant Age Group:	Notes:
Patients	40	Adults	

Thank you for forwarding the completed questionnaire and attached papers.

Having taken note of the information provided, I can confirm that this project will be covered under the terms and conditions of the above policy, subject to written informed consent being obtained from the participating volunteers.

Insurance will only be activated when we have received a copy of the Ethics Committee approval and you must not begin your project prior to this. Please forward a copy of the Ethics Committee approval letter as soon as it is to hand to complete the insurance placement.

If there are any changes to the above details, please advise us as failure to do so may invalidate the insurance.

Yours sincerely

Mrs Ruth McFadyen
Insurance Services Manager
Tel: 023 8059 2417
email: hrm@soton.ac.uk

cc File



Health Research Authority
NRES Committee South Central - Southampton A

Level 3, Block B
Whitefriars
Lewins Mead
Bristol
BS1 2NT

Telephone: 0117 342 1381
Facsimile: 0117 342 0445

22 June 2012

Miss Rokhsaneh Tehrani
Faculty of Health sciences, Building 45,
Postgraduate offices, University of Southampton
Southampton
so17 1b]

Dear Miss Tehrani

Study title: **Speech breathing pattern analysis in patients with chronic respiratory disease before and after attending a pulmonary rehabilitation programme.**

REC reference: **12/SC/0302**

The Research Ethics Committee reviewed the above application at the meeting held on 12 June 2012. Thank you for attending to discuss the study.

Ethical issues raised, resolved or noted in preliminary discussion

1. The Committee thought this was a well written study.
2. The Committee noted that any issue in regards to the participants' dignity was sufficiently managed, as participants would be able to wear outer garments over the top of the belts.
3. The Committee was concerned that telling potential participants that they would have their speech monitored as a result of their breathless might give them something else to unnecessarily worry about. The Committee concluded that anyone involved in the study would already acknowledge that there was a problem, as that would be motivating them to enrol to begin with.

Ethical issues raised by the Committee in private discussion, together with responses given by the researcher

1. The Committee requested clarification as to who the 'responsible individuals' able to look at participants' data would be.

The researcher confirmed that it would only be members of the study research team.

2. The researcher was asked whether she would only be recruiting potential

The researcher explained that she would be including everyone that was enrolled onto the study, and then separating them into groups thereafter.

3. The Committee queried whether the participants would know that there was a potential for breathlessness impacting on speech.

The researcher stated that some participants may have breathlessness, and some may not. What the research team would be looking at specifically is breathing patterns during speech.

4. In reference to 'Appendix 8: An Example of Reading Material for Participants'. The Committee expressed that researchers should make sure participants are able to read before proceeding.

The researcher stated that they would check when the potential participant entered onto the study.

Ethical opinion

The members of the Committee present gave a favourable ethical opinion of the above research on the basis described in the application form, protocol and supporting documentation, subject to the conditions specified below.

Ethical review of research sites

NHS Sites

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

Conditions of the favourable opinion

The favourable opinion is subject to the following conditions being met prior to the start of the study.

1. In reference to the consent form, make the following changes:
 - a. Change the title of the consent form to, 'Participant consent form'.
 - b. Amend point 3 so it reads, '...by responsible individuals Involved in the study from the ...'

Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.

Management permission ("R&D approval") should be sought from all NHS organisations involved in the study in accordance with NHS research governance arrangements.

Guidance on applying for NHS permission for research is available in the Integrated Research Application System or at <http://www.rdforum.nhs.uk>.

For non-NHS sites, site management permission should be obtained in accordance with the procedures of the relevant host organisation.

Sponsors are not required to notify the Committee of approvals from host organisations

It is responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

You should notify the REC in writing once all conditions have been met (except for site approvals from host organisations) and provide copies of any revised documentation with updated version numbers. Confirmation should also be provided to host organisations together with relevant documentation

Approved documents

The documents reviewed and approved at the meeting were:

Document	Version	Date
Evidence of insurance or indemnity		25 April 2012
Investigator CV		02 May 2012
Letter from Sponsor		26 April 2012
Letter of invitation to participant	2	02 May 2012
Other: CV - supervisor		02 May 2012
Other: Patient reply slip	1	02 May 2012
Other: Study confirmation letter	1	02 May 2012
Other: Confirmation of study dates letter	1	02 May 2012
Other: Reading task	1	02 May 2012
Other: Example of open questions for conversation task	1	02 May 2012
Other: St Richard's Hospital patient assessment form	1	02 May 2012
Participant Consent Form	2	02 May 2012
Participant Information Sheet	2	02 May 2012
Protocol	3.1	02 May 2012
Questionnaire: Demographic data form	1	02 May 2012
REC application		02 May 2012
Referees or other scientific critique report		03 April 2012

Membership of the Committee

The members of the Ethics Committee who were present at the meeting are listed on the attached sheet.

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for

The attached document "After ethical review – guidance for researchers" gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Notification of serious breaches of the protocol
- Progress and safety reports
- Notifying the end of the study

The NRES website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

Feedback

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the website.

Further information is available at National Research Ethics Service website > After Review

12/SC/0302

Please quote this number on all correspondence

With the Committee's best wishes for the success of this project

Yours sincerely

PP

Dr Iain Macintosh
Chair

Email: scsha.SWHRECA@nhs.net

*Enclosures: List of names and professions of members who were present at the meeting and those who submitted written comments
"After ethical review – guidance for researchers"*

*Copy to: Miss Rokhsaneh Tehrany
Dr. Martina Prude
Miss Hannah Haines, Western Sussex Hospitals NHS Trust*

Appendix 18 – St. Richards Hospital Research and Development approval letter (study three)



Sussex NHS Research Consortium

Research Consortium Office
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Miss Rokhsaneh Tehrany
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28/06/2012

Dear Miss Tehrany,

Our ID: 1498/NOCI/2012
TITLE: Speech breathing analysis in patients with chronic respiratory disease before and after attending a pulmonary rehabilitation programme.

Thank you for your application to the Sussex NHS Research Consortium for research governance approval of the above named study.

I am pleased to inform you that the study has been approved, and so may proceed. This approval is valid in the following Organisations:

- Western Sussex Hospitals NHS Trust, St. Richard's Hospital, Chichester.

The final list of documents reviewed and approved is as follows:

- Email in response to clarifications (dated 31/05/2012)
- NHS R&D form (submission code: 101686/320835/14/859, signed and dated 02/05/2012)
- NHS Site-Specific Information (SSI) form (submission code: 101686/320800/8/146/147889/242824, signed and dated 17/05/2012)
- Protocol (version 3.1, dated 02/05/2012)
- Participant Invitation Letter (version 2, dated 02/05/2012)
- Participant Information Sheet (version 2, dated 02/05/2012)
- Reply Slip (version 1, dated 02/05/2012)
- Participant Consent Form (version 2.1, dated 02/05/2012)
- Study Confirmation Letter (version 1, dated 02/05/2012)
- Final Confirmation of Study Dates Letter (version 1, dated 02/05/2012)
- Questionnaire: Demographic Data Form (version 1, dated 02/05/2012)
- University of Southampton Confirmation of Sponsorship Letter (signed and dated 26/04/2012)
- University of Southampton Confirmation of Professional Indemnity Letter (signed and dated 25/04/2012)
- CV for Rokhsaneh Tehrany (signed and dated 04/05/2012)
- CV for Dr Anna Barney (signed and dated 08/05/2012)
- CV for Dr Anne Bruton (signed and dated 08/05/2012)
- NRES Committee South Central – Southampton A: letter of favourable ethical opinion with

1. You commence your research within one year of the date of this letter. If you do not begin your work within this time, you will be required to resubmit your application.
2. You notify the Consortium Office should you deviate or make changes to the approved documents.
3. You alert the Consortium Office by contacting me, if significant developments occur as the study progresses, whether in relation to the safety of individuals or to scientific direction.
4. You complete and return the standard annual self-report study monitoring form when requested to do so at the end of each financial year. Failure to do this will result in the suspension of research governance approval.
5. You comply fully with the Department of Health Research Governance Framework, and in particular that you ensure that you are aware of and fully discharge your responsibilities in respect to Data Protection, Health and Safety, financial probity, ethics and scientific quality. You should refer in particular to Sections 3.5 and 3.6 of the Research Governance Framework.
6. You ensure that all information regarding patients or staff remains secure and strictly confidential at all times. You ensure that you understand and comply with the requirements of the NHS Confidentiality Code of Practice, Data Protection Act and Human Rights Act. Unauthorised disclosure of information is an offence and such disclosures may lead to prosecution.

Good luck with your work.

Yours sincerely,



Miss Hannah Haines
Research Governance Officer

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cc.: Mrs Clare Meachin, Research Studies Manager, Western Sussex Hospitals NHS Trust.
Mr Mark Taylor, R&I Projects Manager, Western Sussex Hospitals NHS Trust.

Appendix 19 – Missing data from study three (patients with COPD and bronchiectasis)

Quiet breathing task

	Before PR	During PR	After PR
Missing because of equipment failure	5	6	5
Missing because of participant drop out	0	0	1
Missing (other)	0	0	0
Total no. of missing data sets	5	6	6
Total no. Full data sets	15	14	14

Table 1. Total number of complete data sets available from time point one, two and three during the quiet breathing task

Conversational speech task

	Before PR	During PR	After PR
Missing because of equipment failure	1	5	0
Missing because of study drop out	0	0	1
Missing other	0	0	0
Total no. of missing data sets	1	5	1
Total no. Full data sets	19	15	19

Table 2. Total number of complete data sets available from time point one, two and three during the conversation task

Reading task

	Before PR	During PR	After PR
Missing because of equipment failure	1	5	0
Missing because of study drop out	0	0	1
Missing other	0	0	0
Total no. of missing data sets	1	5	1
Total no. Full data sets	19	15	19

Table 3. Total number of complete data sets available from time point one, two and three during the reading task

Counting task

	Before PR	During PR	After PR
Missing because of equipment failure	1	5	0
Missing because of study drop out	0	0	1
Missing other	0	1	0
Total no. of missing data sets	1	6	1
Total no. Full data sets	19	14	19

Table 4. Total number of complete data sets available from time point one, two and three during the counting task

Appendix 20: Results from the one way repeated measures ANOVA (before, during and after PR)

	Before PR	During PR	After PR	DF	F	<i>p</i>
T _I (sec)	1.59±0.59	1.69±0.44	1.52±0.34	2 ¹	0.69	0.50
T _E (sec)	2.38±0.78	2.40±0.78	2.23±0.52	1.96 ²	0.48	0.61
IM (a.u)	1.25±0.50	1.61±0.69	1.58±0.60	1.98 ²	3.38	0.05
EM (a.u)	1.25±0.51	1.59±0.71	1.56±0.58	1.97 ²	2.85	0.07
T _{tot} (sec)	4.01±1.37	4.08±1.14	3.76±0.81	1.69 ²	0.58	0.54
RR (bpm)	16.33±4.38	15.80±4.50	16.68±3.76	1.87 ²	0.35	0.69
%RC Insp	61.33±11.62	70.45±9.04	67.44±13.13	1.79 ²	3.42	0.05
%AB Insp	38.00±11.83	29.13±8.96	32.02±13.35	1.81 ²	3.23	0.06
%RC Exp	59.74±12.51	68.24±7.39	66.53±12.48	1.56 ²	2.83	0.09
%Ab Exp	39.61±12.65	31.39±7.48	32.97±12.56	1.57 ²	2.66	0.10

T_I (sec) = Inspiration time (seconds); **T_E (sec)** = expiration time (sec); **IM (a.u)** = inspiration magnitude (arbitrary units); **EM (a.u)** = Expiration magnitude (arbitrary units); **T_{tot} (sec)** = breathing cycle time (sec); **RR (bpm)** = respiratory rate (breaths per minute); **RC% Cont Insp** = Ribcage percentage contribution to inspiration; **AB%Cont Insp** = Abdominal percentage contribution to inspiration; **RC% Cont Exp** = Ribcage percentage contribution to expiration; **AB% Cont Exp** = Abdominal percentage contribution to expiration; DF = Degrees of Freedom; ¹Sphericity assumed; ²Greenhouse-Geisser

Before, during and after PR: Mean differences in breathing parameters measured at three different time points during a two minute quiet breathing task in patients with CRD – results of the one way repeated measures ANOVA (n=13)

	Before PR	During PR	After PR	DF	F	<i>p</i>
T_i (sec)	0.66±0.13	0.64±0.11	0.63±0.10	1.63 ²	0.82	0.43
T_e (sec)	3.29±0.77	3.02±0.74	3.06±0.63	1.81 ²	1.98	0.16
IM (a.u)	1.30±0.36	1.46±0.53	1.41±0.60	1.55 ²	0.45	0.59
EM (a.u)	1.29±0.36	1.46±0.54	1.39±0.59	1.58 ²	0.48	0.58
T_{tot} (sec)	3.98±0.82	3.65±0.77	3.72±0.67	1.95 ²	2.08	0.14
RR (bpm)	15.72±3.08	16.99±3.32	16.69±3.01	1.96 ²	2.07	0.15
%RC Insp	61.73±12.03	63.56±13.48	65.28±13.45	1.74 ²	0.49	0.58
%AB Insp	38.00±12.09	36.30±13.47	34.48±13.44	1.76 ²	0.48	0.59
%RC Exp	60.28±15.31	66.46±12.37	65.55±15.61	1.56 ²	1.27	0.29
%Ab Exp	39.57±15.22	33.42±12.49	34.44±16.22	1.57 ²	1.19	0.31

T_i (sec) = Inspiration time (seconds); **T_e (sec)** = expiration time (sec); **IM (a.u)** = inspiration magnitude (arbitrary); **EM (a.u)** = Expiration magnitude (arbitrary); **T_{tot} (sec)** = breathing cycle time (sec); **RR (bpm)** = respiratory rate (breaths per minute); **RC% Cont Insp** = Ribcage percentage contribution to inspiration; **AB%Cont Insp** = Abdominal percentage contribution to inspiration; **RC% Cont Exp** = Ribcage percentage contribution to expiration; **AB% Cont Exp** = Abdominal percentage contribution to expiration; DF = Degrees of Freedom; ¹Sphericity assumed; ²Greenhouse-Geisser

Before, during and after PR: Mean differences in breathing and speech breathing parameters measured at three different time points during a two minute reading task in patients with CRD – results of the one way repeated measures ANOVA (n=14)

	Before PR	During PR	After PR	DF	F	<i>p</i>
T _i (sec)	0.75±0.18	0.77±0.15	0.73±0.16	1.52 ²	0.54	0.54
T _e (sec)	3.97±1.12	4.01±1.36	4.15±1.27	1.81 ²	0.19	0.80
IM (a.u)	1.36±0.60	1.65±0.77	1.66±0.62	2 ¹	1.75	0.20
EM (a.u)	1.34±0.58	1.65±0.78	1.64±0.61	2 ¹	1.87	0.18
T _{tot} (sec)	4.75±1.26	4.79±1.47	4.82±1.13	1.80 ²	0.02	0.96
RR (bpm)	13.44±3.15	13.53±3.76	13.07±3.37	1.82 ²	0.25	0.75
%RC Insp	55.98±13.44	61.35±13.55	16.36±61.36	1.60 ²	1.73	0.20
%AB Insp	43.76±13.38	38.38±13.32	28.36±7.84	1.59 ²	1.77	0.19
%RC Exp	54.92±13.52	61.31±12.81	58.09±16.53	1.56 ²	0.90	0.39
%AB Exp	44.90±13.27	38.35±11.94	41.43±16.55	1.56 ²	0.95	0.38

T_i (sec) = Inspiration time (seconds); T_e (sec) = expiration time (sec); IM (a.u) = inspiration magnitude (arbitrary); EM (a.u) = Expiration magnitude (arbitrary); T_{tot} (sec) = breathing cycle time (sec); RR (bpm) = respiratory rate (breaths per minute); RC% Cont Insp = Ribcage percentage contribution to inspiration; AB%Cont Insp = Abdominal percentage contribution to inspiration; RC% Cont Exp = Ribcage percentage contribution to expiration; AB% Cont Exp = Abdominal percentage contribution to expiration; DF = Degrees of Freedom; ¹Sphericity assumed; ²Greenhouse-Geisser

Before, during and after PR: Mean differences in breathing and speech breathing parameters measured at three different time points during a two minute conversation task – results of the one way repeated measures ANOVA (n=14)

	Before PR	During PR	After PR	DF	F	<i>p</i>
T _i (sec)	0.64±0.27	0.63±0.32	0.52±0.12	1.51 ²	1.27	0.29
T _e (sec)	3.45±1.97	3.57±2.02	3.44±1.57	1.87 ²	0.10	0.88
IM (a.u)	1.06±0.44	1.55±0.34	1.19±0.56	2 ¹	0.31	0.73
EM (a.u)	1.05±0.43	1.14±0.33	1.18±0.55	2 ¹	0.29	0.74
T _{tot} (sec)	4.10±1.95	4.25±2.12	3.97±1.61	1.81 ²	0.41	0.64
RR (bpm)	16.99±5.87	17.19±7.60	17.19±6.60	1.75 ²	0.15	0.97
%RC Insp	54.48±11.37	65.91±11.56	64.60±13.05	1.59 ²	3.73	0.05
%AB Insp	45.09±11.43	34.61±11.61	35.22±13.09	1.60 ²	3.54	0.05
%RC Exp	55.50±10.87	65.86±13.01	61.06±12.06	1.74 ²	2.69	0.09
%Ab Exp	44.11±11.04	34.33±13.07	38.57±11.94	1.77 ²	2.40	0.11

TI (sec) = Inspiration time (seconds); TE (sec) = expiration time (sec); IM (a.u) = inspiration magnitude (arbitrary); EM (a.u) = Expiration magnitude (arbitrary); T_{tot} (sec) = breathing cycle time (sec); RR (bpm) = respiratory rate (breaths per minute); RC% Cont Insp = Ribcage percentage contribution to inspiration; AB%Cont Insp = Abdominal percentage contribution to inspiration; RC% Cont Exp = Ribcage percentage contribution to expiration; AB% Cont Exp = Abdominal percentage contribution to expiration; DF = Degrees of Freedom; ¹Sphericity assumed; ²Greenhouse-Geisser

Before, during and after PR: Mean differences in breathing and speech breathing parameters measured at three different time points during a two minute counting task – results of the one way repeated measures ANOVA (n=14)

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