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Simultaneous measurement of force and respiratory profiles during chest physiotherapy in ventilated children

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Abstract
There are currently no objective means of quantifying chest wall vibrations during manual physiotherapy. The aims of the study were to (i) develop a method to quantify physiotherapy-applied forces and simultaneous changes in respiratory flow and pressure, (ii) assess the feasibility of using this method in ventilated children and (iii) characterize treatment profiles delivered by physiotherapists in the paediatric intensive care unit. Customized sensing mats were designed and used in combination with a respiratory profile monitor. Software was developed to align force and flow data streams. Force and respiratory data were successfully collected in 55 children (median age 1.6 years (range 0.02–13.7 years)). Physiotherapists demonstrated distinctive variations in the pattern of force applied and manual lung inflations. The maximum applied force ranged from 15 to 172 N, and was correlated with the child's age ($r = 0.76$). Peak expiratory flow increased significantly during manual inflations both with and without chest wall vibrations ($p < 0.05$). This method provides the basis for objective assessments of the direct and independent effects of vibration forces and manual lung inflations as an essential precursor to developing evidence-based practice.

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Keywords: physical therapy modalities, chest wall oscillation, respiratory therapy, intensive care, child, measurement technique

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1. Introduction

Respiratory physiotherapy is considered to be an important component in the management of ventilated patients in intensive care (American College of Critical Care Medicine of the Society of Critical Care Medicine 1999, Ferdinande 1997). In the UK, physiotherapy treatments often involve either manual or ventilator inflation of the patient's lungs, interspersed with the application of manual 'chest wall vibrations'. Chest wall vibrations (CWV) involve the application of a rapid extra thoracic compressive force at the beginning of expiration, followed by oscillatory compressions until expiration is complete. The vibrations are thought to simulate a cough or 'huff', propelling secretions into the large airways, for removal by suction or cough (McCarren and Alison 2006).

Techniques involving the application of forces to the chest wall for the treatment of respiratory conditions were first documented almost a century ago (MacMahon 1915, Opie and Spalding 1958). However, the techniques remain largely unquantified and may vary between practitioners and units. The terms chest vibrations, compressions, shaking and expiratory flow increase techniques have variously been used in the literature (Almeida *et al* 2005, Wong *et al* 2003, Sutton *et al* 1985), but not objectively defined. Since there may be overlap between these, the general term 'chest wall vibrations' in this paper will encompass all compressive manoeuvres applied in physiotherapy treatments during expiration. The compressions and oscillations applied during CWV are believed to aid secretion clearance. A number of physiological mechanisms have been proposed, including increasing absolute peak expiratory flow and increasing the expiratory bias of airflow to move secretions towards the oropharynx (Gross *et al* 1985, King 1998, King *et al* 1983, Ntoumenopoulos 2005, van der Schans *et al* 1999, Wanner 1984). In patients with excessive bronchial secretions, mucus clearance can be achieved by two-phase gas liquid mechanisms, with biased tidal breathing favouring the expiratory flow. In addition, such clearance can be further promoted by changing the rheological properties of mucus (App *et al* 1998, Clarke *et al* 1970, Kim *et al* 1987, Sackner and Kim 1987).

In order to evaluate the efficacy of any manual therapy, it is important to have a means of quantifying such treatment. It is challenging to measure techniques which involve manual contact between the therapist and patient. Recent attempts to objectively characterize CWV have utilized instrumented treatment beds (Blazey *et al* 1998, McCarren *et al* 2006). These indirectly measured the force applied to the chest wall through force plates in the bed beneath the patient. While these innovations successfully assessed force application by therapists on healthy volunteers, they did not directly measure the force applied through the hand. Furthermore, they cannot easily be used in clinical environments such as intensive care.

The effectiveness of respiratory physiotherapy in mechanically ventilated patients is likely to be influenced by the interaction between different treatment components such as CWV and lung inflations. It is therefore essential to assess the forces applied during CWV with simultaneous changes in air flow in the lungs.

The aims of this study were to

- develop a method of quantifying CWV forces and a means of evaluating simultaneous changes in respiratory flow and pressure;

- assess the feasibility of using the measuring system in a population of critically ill, mechanically ventilated children;
- characterize the magnitude and pattern of forces applied during CWV and evaluate the direct effects of these manoeuvres on flow, volume and pressure changes in the lungs.

2. Methods

2.1. Development of a technique for simultaneous measurement of chest physiotherapy forces and respiration

In preliminary laboratory studies, six paediatric physiotherapists simulated CWV techniques on a firm convex foam surface. Magnitude and pattern of force were recorded using a force plate and dynamometer (Type UF2, Pioden Controls Ltd). Results suggested that an appropriate force sensing system needed an operational range of 10–200 N and a sampling frequency greater than 24 Hz.

The novel pliance® system (novel *gmbh*, Munich, Germany) was identified as a suitable commercially available technology upon which the measurement technique could be based. This system measured dynamic pressure distributions and force by means of a number of individually calibrated capacitive sensors arranged in a matrix. Based on our templates and specifications, the company produced two custom-made elastic, flexible, L-shaped sensor mats, one small (24×20 cm^2 for use with infants and children under 8 years) and one large (25×25 cm^2 for use with children over 8 years and adults). These operated at a sampling frequency of 50 Hz over a range of 0.2–15 N cm^{-2}. This equates to a force range between 10 and 660 N when forces are applied by an average-sized hand with a contact area of 44 cm^2 (7.5 cm diameter). The entire system comprised the mats, pliance® analyser as an electronic interface and a desktop or notebook computer with pliance® data acquisition software (figure 1). Incorporation of Bluetooth™ telemetry removed any hard-wire connection between the sensing mats and either the computer or mains voltage.

The following laboratory tests were undertaken on both mats to assess the dynamic and static performance and accuracy of the force sensing mats and novel pliance® system.

- Dynamic response was investigated by imposing step and cyclic loading using a computer-controlled servo-hydraulic dynamic testing unit (Instron 8874®). The sensor mats were cyclically loaded between 10 and 500 N at frequencies ranging from 0.1 Hz to 50 Hz.
- Accuracy and precision of the sensor mats were evaluated by repeated random manual loadings using calibration weights up to 200 N, the estimated range of paediatric physiotherapy force application. The Instron® was additionally used to load the mat from 50 to 500 N.
- To explore the effect of laying the mat around the child's convex chest wall, the mats were subjected to extreme manual curvature (forming a cylinder of 6.5 cm diameter).
- The margin of error resulting from sustained application of a 50 N force over a 1 h period was evaluated.

Descriptive parameters of the physiotherapy force profiles were identified from pilot data. Using the summary ASCII format file (comprising time and force data) generated by the pliance® system, algorithms and an analysis programme were devised in-house in Labview®. Summary analyses were calculated for the following force parameters (figure 2):

- baseline force—force applied at the point identified as the start of a CWV,
- maximum force—force occurring anywhere between the start and end of an individual CWV,

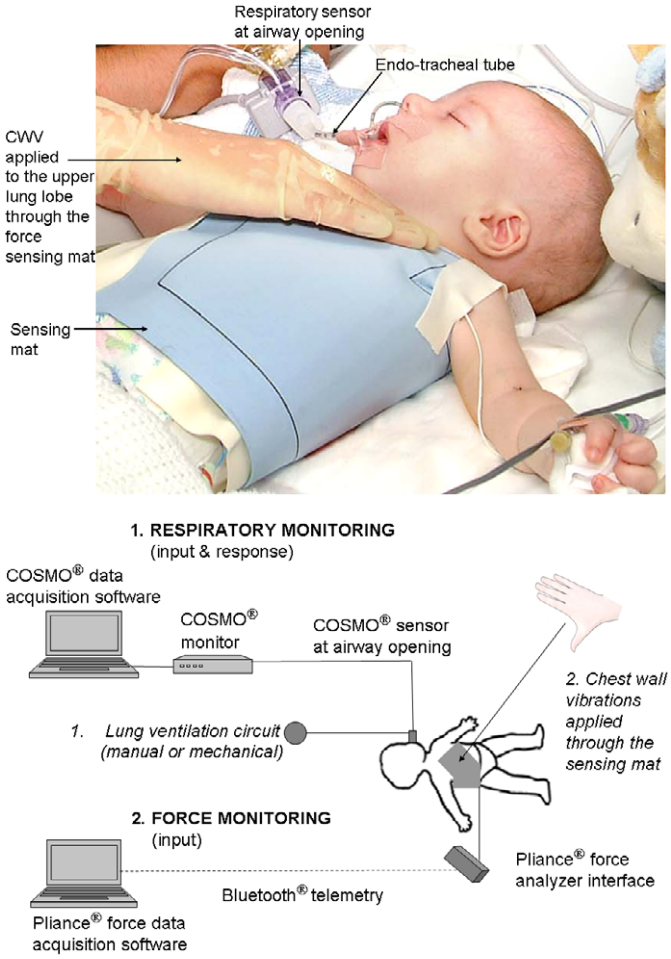

Figure 1. Photograph and schematic representation of the equipment required for simultaneous force and respiratory measurements in mechanically ventilated children. Lung ventilation switched from mechanical during baseline measurements to manual during physiotherapy.

(This figure is in colour only in the electronic version)

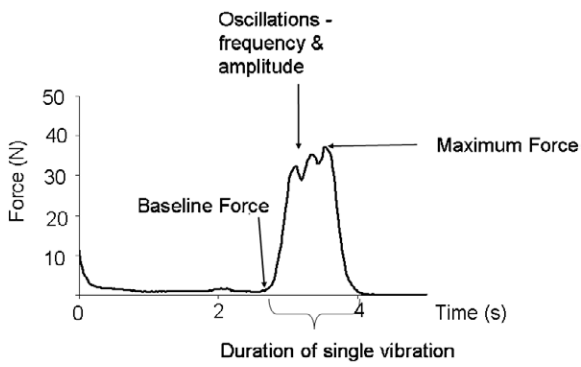

Figure 2. Parameters defined to characterize chest wall vibration force profiles.

- mean force—mean force applied over 1 s (area under curve/CWV duration),
- frequency and amplitude of oscillations—derived from the inward compressive oscillations,
- duration of each vibration,
- duration of the entire treatment.

The CO_2SMO® Plus! Respiratory Profile Monitor (Respironics, Wallingford CT, USA) was identified as a suitable tool for measuring simultaneous airflow and pressure at the airway opening (sampling frequency of 100 Hz). Both the neonatal and paediatric sensors have previously been validated in our department (Castle *et al* 2002, Main *et al* 2001, Main and Stocks 2004).

Additional software was developed in Labview® to align and overlay the force and respiratory data streams, enabling simultaneous measurement of respiratory changes during both CWV and lung inflations.

2.2. *Clinical study measuring chest physiotherapy treatments and simultaneous respiratory changes in mechanically ventilated children*

A clinical study was conducted in mechanically ventilated children requiring chest physiotherapy in the intensive care units of Great Ormond Street Hospital for Children, London. Approval for the study was granted by the Central Office for Research Ethics Committees (COREC). Written, informed consent was obtained from all participating families and physiotherapists.

2.2.1. Inclusion criteria. Mechanically ventilated children (0–16 years of age), who were cardiovascularly stable and required chest physiotherapy, were eligible for recruitment. Clinical indications for physiotherapy included changes on chest radiograph, added or decreased breath sounds on auscultation, increased ventilatory requirements and/or deteriorating blood gases.

2.2.2. Exclusion criteria. Children at risk of haemorrhage, with osteoporosis or whose medical instability precluded physiotherapy treatment, were excluded, as were those children with a tracheal tube leak >20% (Castle *et al* 2002, Main *et al* 2001). Tracheal tube leak was calculated as the percentage difference between the inspired and expired tidal volumes.

2.2.3. Equipment (figure 1). The pliance® system and customized mats detailed in section 2.1 were used to record force data. The non-invasive CO_2SMO® Plus! Respiratory Profile Monitor (Respironics, Wallingford CT, USA) measured airflow and pressure at the airway opening continuously and instantaneously via a disposable, fixed-orifice, differential flow and pressure sensor inserted between the endo-tracheal tube and the ventilator or manual lung inflation circuit. Inspired and expired volume data were derived by integrating flow over time. The CO_2SMO® has been previously validated in mechanically ventilated children (Main and Stocks 2004). A neonatal sensor was used for children less than 2 years of age (where airflows were generally <25 L min^{-1}) and a paediatric sensor for older children.

2.2.4. Protocol. Baseline respiratory data, during normal mechanical ventilation, were recorded for 15 min prior to the physiotherapy session, using the CO_2SMO® monitor. Tracheal tube leak was assessed and data excluded if leaks remained above 20% despite repositioning

the child (Castle *et al* 2002, Main *et al* 2001, Main and Stocks 2004). Respiratory flow, pressure and volume were recorded.

The lightweight sensing mat was taped over the treatment area of the child's chest. Force and flow data (before, during and after physiotherapy) were synchronized using a small, reinflating bladder, depression of which generated simultaneous force and flow signals. Following initial data registration, the CO_2SMO® sensor was reconnected into the child's ventilator circuit and the entire physiotherapy session was continuously recorded using the sensing mat and CO_2SMO®. The CO_2SMO® sensor was removed from the patient circuit and disconnected from the CO_2SMO® monitor during saline instillation and suctioning.

Chest physiotherapy was delivered by the intensive care physiotherapist, who selected her treatment techniques based on assessment of clinical indications. Treatment notes to document periods of manual lung inflations, CWV, saline instillation and suction were continuously timed and electronically entered into the CO_2SMO®. Respiratory data collection continued for up to 1 h following the chest physiotherapy, in the absence of any other interventions.

Video footage of the protocol procedure is available in the online version of this journal, see stacks.iop.org/PM/28/1017

2.2.5. Statistical analysis. Median values and ranges were used to describe the clinical force data. One-way repeated measures analysis of variance tests were used to compare changes from baseline in peak expiratory flow, inspired volume and peak inflation pressure. The flows and volumes were weight corrected to allow comparison of data across the age range. Differences between measurement conditions were considered significant when $p < 0.05$. As a result of non-normally distributed force data (as shown by a test of normality), Spearman's rank correlation coefficient was used to assess the relationship between age and the maximum applied force during chest physiotherapy.

3. Results

3.1. Laboratory evaluation of the novel pliance® *system and custom-made sensing mats (which shared the same sensor characteristics)*

- Step and cyclic loading of the mat demonstrated a frequency response up to 38 Hz (−3 dB cut-off).
- During repeated, random loadings between 14.7 N and 54.9 N, the mean (95% confidence interval, CI) difference between measured and applied forces was −0.53 N (−0.36 N to −0.7 N), with a maximum error of −1.65 N. The average coefficient of variation during these *in vitro* assessments was 2.7% (range 1.4% to 4.1%). Assessments of forces up to 200 N revealed that the measurement error was proportional to the applied force, and was therefore expressed as % differences. The mean % error (95% CI) was −4.7% (−3.7% to −5.7%), the maximum error equating to −6.3%. Similarly, when loading up to 500 N with the Instron®, the mean % error was −4.5% (maximum −7.7%).
- The maximum force generated by extreme curvature of the unloaded mat was 1 N.
- The margin of error for 50 N loading over 1 h was +3%.

The software written in-house to (i) analyse the force profiles, (ii) integrate the force and respiratory data streams successfully characterized the profiles applied and aligned the two inputs by the registration signals (figure 3). By this method, it was possible to measure the direct breath-by-breath effects of applied forces on airflow and compare these with baseline respiratory parameters.

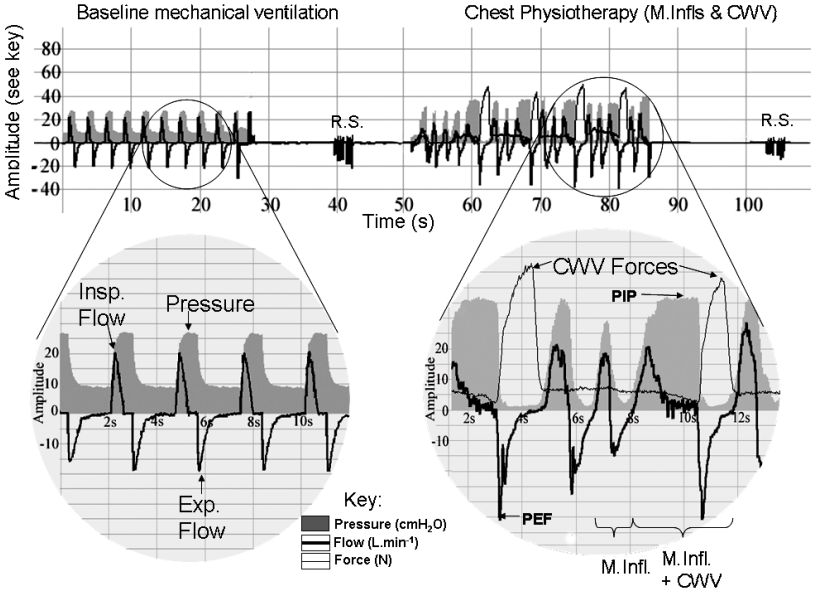

Figure 3. Force and simultaneous respiratory changes aligned by analysis software. The upper panel shows representative data from a physiotherapy treatment of a child aged 5 years, including baseline mechanical ventilation. Physiotherapy comprised manual inflations (M.Infls) interspersed with chest wall vibrations (CWV). The lower panels show in detail baseline ventilator respiration and the pressure and flow changes occurring during a 14 s snapshot of manual inflations with two CWV applied during expiration. R.S: registration signals; PEF: peak expiratory flow; PIP: peak inflation pressure; Insp./Exp.: inspiratory/expiratory.

3.2. Clinical measurement of force and respiration in the intensive care unit

Fifty five children with a range of clinical diagnoses (30 males, median age 1.6 (range 0.02 to 13.7) years, with 35 aged <2 years) were recruited to the study. Of the 35 under 2 years, 18 had undergone cardiac surgery. Twelve respiratory physiotherapists delivered the treatments.

Data were successfully collected in all children recruited, and the non-invasive measurements proved to be acceptable both to the children's families and health professionals, with no adverse events recorded. The analysis software was used successfully in all participants.

Figure 3 illustrates a typical example of force and respiratory data, from the treatment of a 5 year old boy. It is clear that the flows and pressures generated at the airway opening during physiotherapy treatment were substantially different from those measured during baseline mechanical ventilation. Physiotherapy manual lung inflations when CWV forces were applied (M.Infls + CWV) were analysed separately from the remaining lung inflations. Peak expiratory flow doubled from 19 L min^{-1} during baseline ventilation to 40 L min^{-1} during the inflations with vibrations. Peak inflation pressure also increased from 22 to 35 cm H_2O. Analysis of variance of data from all 55 children showed that there was a consistent, significant increase in peak expiratory flow during manual inflations with and without vibrations compared with baseline ventilation. Peak inflation pressure and inspired volume mirrored the significant increases seen in peak expiratory flow (figure 4).

There were clear differences in the force–time profiles applied by individual physiotherapists. This is exemplified by figure 5, which describes four different physiotherapists treating four infants below 15 months of age. Differences were noted in terms of the magnitude of applied force, number and frequency of oscillations and duration of

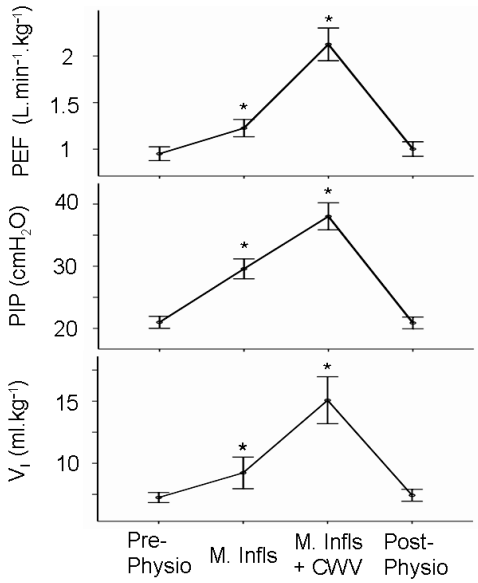

Figure 4. Mean and 95% CI change in weight-corrected peak expiratory flow (PEF), peak inflation pressure (PIP) and weight-corrected inspired volume (V_I) in 55 mechanically ventilated children during the manual lung inflations (M. Infls) with and without vibrations (CWV), compared with baseline mechanical ventilation before and after the physiotherapy treatment. $^*p < 0.05$.

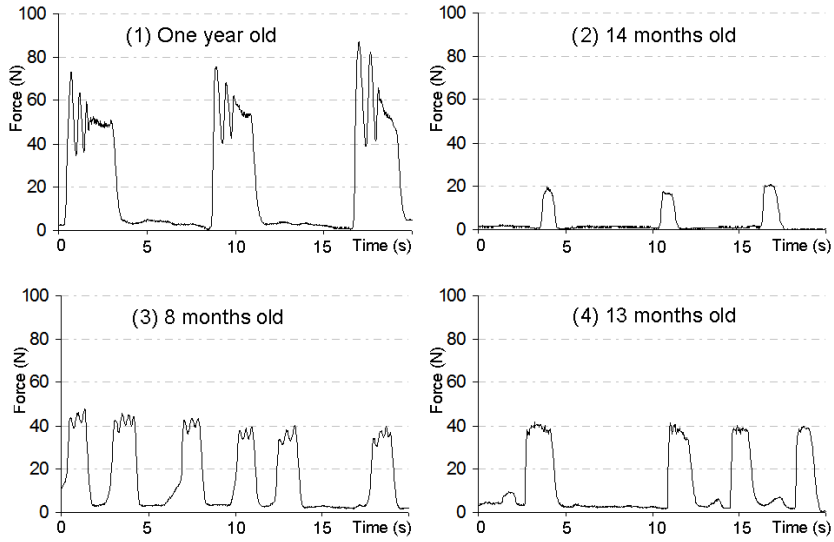

Figure 5. Variations in the style of force profiles delivered to four different infants aged below 15 months by four different physiotherapists.

each CWV. The maximum force in profile 1 was four times greater than that in profile 2 and double that seen in profiles 3 and 4. Force profile 2 had no oscillatory component, whereas profile 3 shows several distinct small amplitude oscillations. In profile 1 the oscillations were more marked, whilst in profile 4 the low amplitude oscillations occurred at a greater frequency. However, there was consistency of CWV force profile within each treatment.

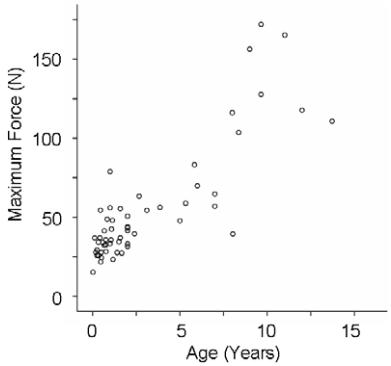

Figure 6. Relationship between maximum force during chest physiotherapy and age in 55 ventilated children $r = 0.76$, $p < 0.001$.

Table 1. Median (range) of chest wall force parameters encountered during physiotherapy treatments in 55 ventilated children.

Parameter	Median (range)
Maximum force (N)	41 (15–172)
Mean force (N)	27 (9–110)
Baseline force (N)	3 (0–16)
Frequency of oscillations (Hz)	3 (0–11)
Amplitude of oscillations (N)	5 (0.1–56)
Duration of single vibration (s)	2 (0.8–4.6)
Duration of entire treatment (min)	6.2 (1.6–25)

The forces encountered in the study (table 1) were within the range predicted when designing the force characterization method (section 2.1). Magnitude of maximum and mean force applied increased with age ($r = 0.76$ and 0.75, respectively), see figure 6. Forces greater than 85 N were only delivered to children over the age of 8 years. Whilst forces increased with age, each physiotherapist's 'signature' force–time profile remained consistent within a treatment in terms of frequency and amplitude of oscillation, and duration of vibration.

4. Discussion

Extensive development and subsequent validation of both force sensing mats and the accompanying software have successfully enabled characterization of the forces applied during physiotherapy. Furthermore, we have shown that it is feasible to measure changes of flow and volume during treatment and to relate these changes in flows and volumes to the applied force. In contrast to previously described force measuring systems, the current mat is eminently suitable for use in the clinical environment, including the intensive care environment, proving acceptable to both families and health professionals. The clinical study suggested that expiratory flows increased significantly during CWV compared with baseline and manual inflations alone; inflation pressures and volumes similarly increased. Substantial variation between physiotherapists was observed, in terms of magnitude and pattern of forces applied, but a consistency within individual physiotherapy treatments. There also appeared to be a positive linear relationship between the force applied and the age of the child. The software developed for the mat allows characterization not only of the maximum and mean force, but

also of the amplitude and frequency of oscillations and duration of the entire event (figures 2 and 5). This will provide a vital basis for objectively ascertaining the relative contributions of these variables in determining the effectiveness of physiotherapy in different populations and environments. The current system is ideally suited to quantify the most commonly used technique of chest wall vibrations, and the variability reported in this technique (Main *et al* 2004, McCarren *et al* 2006, van der Schans *et al* 1999). Further work is required to adapt the technology to sample the lower forces delivered during chest percussions and the higher frequencies of mechanical chest wall vibrations.

The integrated technique using the force sensor mat and respiratory data allowed direct measurement of the way in which component parts of chest physiotherapy (manual inflations and CWV) could facilitate secretion removal and enhance respiratory function. Previous physiotherapy studies using the CO_2SMO® respiratory monitor involved measurements taken before and after physiotherapy treatments since there had been anxieties relating to flow signal distortion and sampling frequency during the physiotherapy treatment (Main *et al* 2004, Main and Stocks 2004). These concerns proved to be insignificant, and the quantification of changes in flow and pressure at the airway opening during treatment provided important information about direct therapeutic effects. It was possible to differentiate expiratory flow occurring during manual inflations alone from those during which CWV forces were applied. Respiratory data collected during physiotherapy revealed a significant increase in peak expiratory flow from baseline during manual inflation breaths, with a further significant increase during manual inflations combined with CWV. Peak expiratory flow is influenced by the driving pressure within the lungs, which relates to the inspired volumes and pressures in the airways. Manual lung hyperinflations can independently enhance secretion clearance, by generating an increase in elastic recoil and an increase in expiratory flow, driving mucus out along the respiratory tract (Ntoumenopoulos 2005). In this study, the increase recorded in inspired volumes and peak inflation pressures would have increased lung elastic recoil. The data suggest that the application of extra-thoracic forces further augment the expiratory flow bias generated by lung inflations alone.

The range of maximum forces encountered in this clinical paediatric study were comparable with those reported in a study using an instrumented bed to monitor the treatment of a healthy adult (peak force 137.1 N (SD 66.7), McCarren *et al* 2006). The ranges recorded in this study originated from the treatment of 55 patients by 12 different physiotherapists. Repeatability studies are in progress to examine the variation between and within physiotherapists when treating the same and different subjects, as a framework for understanding treatment variability.

The variations in the force–time profile between physiotherapists pose questions with respect to the relative efficacy of different styles of treatment and the importance of the individual components of the force profile on air flow and airway clearance. It may be assumed that the early rapid compression force is responsible for the increase in expiratory airflow and that the oscillatory component is more important in terms of altering the mucus properties. An increase in mucus transport has been linked to increased airway oscillation, which is believed to decrease the viscosity of mucus and increase the expiratory air flow (Chang *et al* 1988, Gross *et al* 1985, King *et al* 1990). The exact relationship between applied force and resultant flow changes will be determined by a number of factors including the timing of applied force during the respiratory cycle, age of the child and underlying pathophysiology which will need to be explored thoroughly in future clinical studies.

The clinical results obtained in mechanically ventilated children in intensive care have demonstrated a positive relationship between force application and the patient's age, and the existence of different physiotherapy styles when delivering CWV forces. The increase in the

magnitude of force applied by physiotherapists to older children may relate to an increasing stiffness (decreasing compliance) of the chest wall that occurs through the course of childhood. This in turn may influence the transmission of force to the lungs. A study is currently being undertaken to explore the extent to which variation in force and respiratory parameters are influenced by age, body size and pathophysiology of patients, as well as the experience of the practitioner and the coordination between manual inflations and CWV. Multivariate analyses may help to differentiate the independent effects of lung inflation techniques from CWV forces, in explaining changes in expiratory airflow. It is possible that while individual physiotherapists' treatment styles remained consistent, the magnitude of applied force was adjusted according to the patient's age and clinical state.

The integration of force and flow measurements using the analysis software and mats devised in this study provides a unique opportunity to clarify the mechanisms underlying the skill of chest physiotherapy. This technique was developed to facilitate accurate measurements of physiotherapy for ventilated children on the intensive care unit. However, it would be equally applicable for ventilated adults and in spontaneously breathing patients of all ages. This measurement approach may also provide an objective teaching aid for professionals and carers, both in the clinical/academic environment and in the community. Wider applications exist in the field of resuscitation training, in terms of both modifying the system for evaluation of the forces applied during cardio-pulmonary resuscitation and monitoring lung recruitment techniques during manual lung hyperinflations.

5. Conclusions

This novel, integrated technique measures applied forces during physiotherapy treatment combined with changes in flow and pressure at the airway opening. Such an approach enables a fundamental exploration of chest wall vibrations and manual lung inflations. The wide spectrum of physiotherapy practice observed in this study with respect to manual inflations and force profiles may reflect a number of factors including the timing of applied force during the respiratory cycle, age of the child and underlying pathophysiology. Such factors will need to be explored thoroughly in future clinical trials. Clinical studies incorporating this technique will allow physiotherapists to explore objectively why some treatments enhance respiratory function whilst others do not, providing an important tool to develop evidence-based practice.

The integrated system also has a wide potential application in teaching and training of both health professionals and family members giving chest physiotherapy at home; this could greatly facilitate delivery of optimal treatment for patients in the future.

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