UNIVERSITY OF SOUTHAMPTON

EFFECT OF HAND-TRANSMITTED VIBRATION ON FINGER BLOOD FLOW

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ABSTRACT

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Background: Long-term exposure to hand-transmitted vibration can result in the signs and symptoms of vibration-induced white finger (VWF), characterised by attacks of blanching resulting from reduced digital blood flow during and after exposure to cold. Experimental studies have found that acute exposure of a hand to vibration reduces finger blood flow (FBF) during exposure. After exposure, FBF is reported to immediately increase but subsequently reduce. A weaker response has been reported in an unexposed contralateral hand, suggesting the response in the exposed hand is mediated by central and local mechanisms, whereas the response in the unexposed hand is centrally mediated. The responses during and after exposure to vibration may be separate phenomena and may depend differently on the frequency, magnitude and the duration of the vibration exposure. This thesis seeks to improve understanding of the acute effects of the magnitude and frequency of hand-transmitted vibration on FBF during and after vibration exposure.

Method: Three experiments were designed to examine variables likely to affect the accuracy of measuring FBF by venous occlusion plethysmography. In a further four experiments, FBF was measured before, during and after the application of a 2 N force and vibration at 16, 31.5, 63, 125, 250, and 315 Hz at acceleration magnitudes from 0 to 15 ms^{-2} r.m.s. Healthy male subjects were used in all experiments.

Results: In the first experiment in Chapter 4, FBF was found to be similar whether measured on a single finger or simultaneously on all five fingers of a hand. Variations in the occlusion pressure influenced the rate of change in finger volume, and the height of the hand relative to the heart affected the measured blood flow, but all measurements were repeatable.

Differences in FBF between two plethysmographs (Medimatic Digitmatic DM2000 and *HVLab* multi-channel plethysmograph) found in the second experiment in Chapter 4, were partially explained by the compensation for the resistances of the cables connected to the strain gauges.

The third experiment, in Appendix B, found no effect on FBF of whole-body vibration (1.0 ms^{-2} r.m.s. at 8 Hz or 4 ms^{-2} r.m.s. at 63 Hz) during or after vibration. Exposure to whole-body vibration prior to an experimental session should not affect the measured FBF.

The experiments in Chapters 5 and 6 found that a 2 N push force applied to the finger reduced FBF in the exposed finger, compared to pre-exposure blood flow. However, a 2 N push force applied to one or two palms did not affect FBF in either hand.

With the effect of push force minimised in the experiments in Chapters 6 to 8 there was no difference in FBF between the exposed and the unexposed hand during or after exposure to vibration. Also, there was vasoconstriction without preliminary strong vasodilation after the end of exposure.

At all frequencies, the reduction in blood flow was proportional to the magnitude of the vibration over the range of magnitudes investigated.

The experiments in Chapters 6 and 7 found that over the range of frequencies investigated (16 to 315 Hz) the higher frequencies of hand-transmitted vibration caused a stronger vasoconstriction than lower frequencies, both during and after vibration exposure.

Vibration of two hands generally caused a similar vasoconstriction as vibration of one hand in Chapter 8.

The results are consistent with vibration activating centrally mediated vasoconstriction in both hands during and after vibration exposure. The mechanism controlling the vasoconstriction is dependent on the frequency and the magnitude of the vibration.

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CONTENTS

CHAPTER 1

INTRODUCTION

Many people use hand-held vibrating tools in the workplace. Long-term exposure to hand-transmitted vibration can result in the signs and symptoms of vibration-induced white finger (VWF), characterised by attacks of blanching resulting from reduced digital blood flow during and after exposure to cold. Blanching is defined as a white appearance or withdrawal of normal colour (Griffin, 1990).

Injury may be avoided if the relationship between the vibration exposure and the vascular response was clear. Understanding the sensitivity of the body to vibration can assist in the control of high risk vibration exposure to workers. Limiting the duration of vibration exposure, exposure to high risk frequencies, magnitudes and directions of vibration via tool design and working practices can contribute to reducing the vibration risk to employees.

The effects of long-term and short-term exposure to hand-transmitted vibration are not identical. The long-term (i.e. chronic) effects of hand-transmitted vibration are difficult to study and do not allow the determination of how the effects depend on the characteristics of vibration. Although the effects of short-term (i.e. acute) exposure to hand-transmitted vibration do not yield the same signs and symptoms as long-term exposure, the study of the acute effects of vibration may provide an understanding of how the body reacts to exposure to vibration. Studies of the acute effect may therefore assist the understanding of the chronic effects.

At present it is not possible to predict accurately using a simple method, the severity of the vascular response to vibration magnitude, frequency and duration. ISO 5349 (2001) uses a frequency-weighting and 8 hour energy equivalent frequency-weighted r.m.s. acceleration to represent the assumed dependence on vibration frequency of the human response to vibration and to predict a dose-response relation for the prevalence of vibration-induced white finger but this method is not proven. Chapter 2 presents a review of the literature of studies investigating the chronic and acute responses to hand-transmitted vibration. Experimental studies have found that acute exposure of a hand to vibration and push force reduces finger blood flow (FBF) during exposure. After exposure, FBF is reported to immediately increase but

subsequently reduce. A weaker response has been reported in an unexposed contralateral hand, suggesting the response in the exposed hand is mediated by central and local mechanisms, whereas the response in the unexposed hand is centrally mediated. The responses during and after exposure to vibration may be separate phenomena and depend differently on the frequency, magnitude and duration of the vibration exposure. Chapter 2 outlines the objectives and hypotheses of this thesis.

This thesis aims to try to understand the effect of vibration on finger blood flow by investigating it's dependence on vibration frequency and magnitude.

The hypotheses underlying this research are:

a. Previous observations of the effect of vibration on finger blood flow have been confounded by the effect of push force;

b. Increasing the magnitude of vibration will reduce the finger blood flow;

c. The reduction in finger blood flow is dependent on the frequency of the vibration;

d. Vibration will produce the same reduction in finger blood flow in exposed and unexposed hands.

Chapter 3 describes the apparatus used to vibrate the fingers and to measure finger blood flow.

Chapter 4 details the venous occlusion method of finger blood flow measurement and experimentally investigates the parameters of the test for reliable measurement. Two plethysmographs are compared.

In Chapter 5 to Chapter 8, four experiments are described. Table 1-1 lists the main variables investigated in each experiment.

Chapter 5 examines the influence on finger blood flow of a 2-N push force to the finger. Vibration was applied at 125 Hz at magnitudes from 0 to 11 ms^{-2} r.m.s. (frequency-weighted).

In Chapter 6 a pilot study compares the finger blood flow during push force to either the finger or the palm. Ten vibration conditions at frequencies from 16 to 250 Hz with vibration magnitudes of 0 to 15 ms^{-2} r.m.s. and two no-vibration control conditions were used to investigate whether the location of push force affects finger blood flow during vibration and after vibration.

In the experiment described in Chapter 7 vibration and push force were applied to the palm. The dependence of finger blood flow on vibration frequency and magnitude were examined with exposure of one hand to vibration at six frequencies from 16 to 315 Hz with vibration magnitudes of 0 to 15 ms^{-2} r.m.s. (frequency-weighted) with constant velocity.

Table 1-1 The main variables investigated in each experimental chapter of the thesis

Chapter	Frequency (Hz)	Magnitude (ms^{-2} r.m.s.) Frequency-weighted	Push force (2 N) location	Number of sites vibrated
4 Experimental study: Venous occlusion plethysmography	n/a	n/a	n/a	n/a
5 Experimental study	125	Ramped magnitude 0-11	Finger	Vibration to one hand
6 Experimental pilot study	16 – 250	Ramped magnitude 0-15	Finger or palm	Vibration to one hand
7 Experimental study	16 – 315	Ramped magnitude 0-15	Palm	Vibration to one hand
8 Experimental study	31.5 125	5.5, 11, 22 (Unweighted)	Right palm and left palm	Vibration to one or two hands
Appendix B Experimental study	8 63	1 4		Whole body vibration

The experiment described in Chapter 8 compared vasoconstriction during vibration of one hand with the vasoconstriction during vibration of two hands, at three acceleration magnitudes and at two frequencies.

In Chapters 5 to 8, the finger blood flow in the exposed and unexposed hand was compared to investigate whether vibration to one hand affected the other unexposed hand. The finger blood flow during and after vibration exposure was examined in relation to the vibration characteristics and the location of the push force.

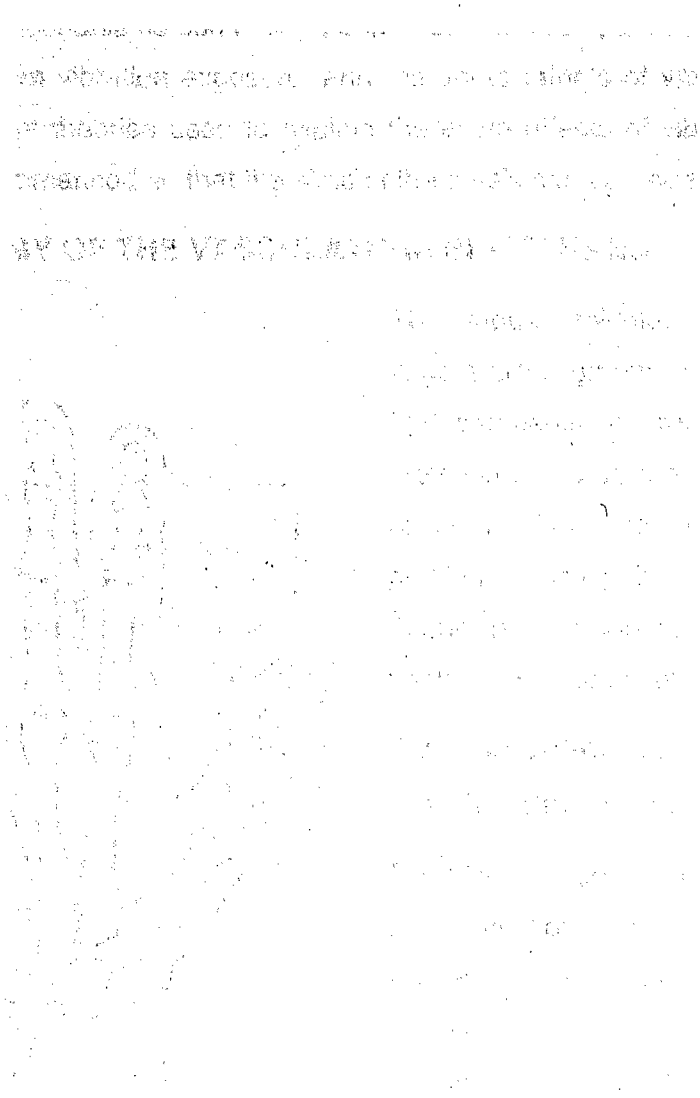
A further experiment was conducted to investigate whether exposure to whole-body vibration affects peripheral blood flow and could influence the data collected during the experiments. This experiment is presented in Appendix B.

Chapter 9 presents a discussion of the findings within the context of the research area and considers how the findings presented in this thesis challenge past assumptions. The discussion also presents a representation of the relationship

between short-term exposure to hand-transmitted vibration and finger blood flow. Some suggestions for future work are also outlined.

Chapter 10 presents the general conclusions of the research.

Appendix A contains the subject medical questionnaire and instructions to subjects to avoid stimulants before each experimental session.



CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This literature review encompasses the anatomy and physiology of the blood vessels in the hand, the mechanisms controlling peripheral blood flow, a consideration of the effects of long-term vibration exposure, and the acute effects of vibration on finger blood flow. Current theories used to explain the acute effects of vibration on finger blood flow are summarised so that the aims of the thesis can be understood.

2.2 ANATOMY OF THE VASCULATURE IN THE HAND

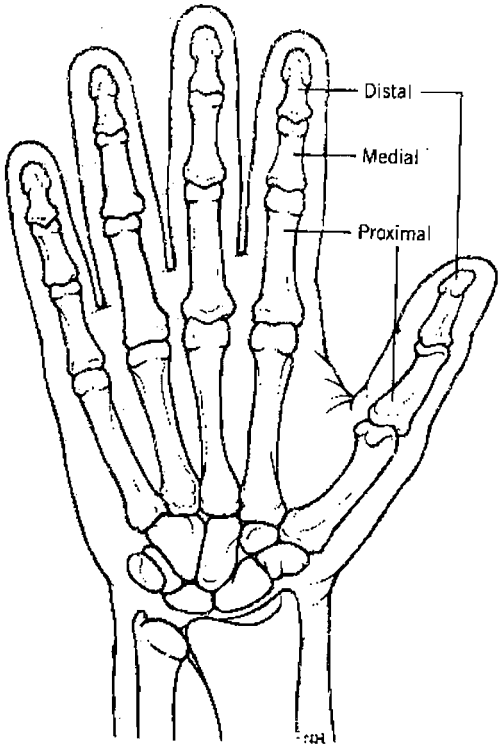


Figure 2-1 Phalanges of the digit (Churchill's Medical Dictionary, 1989)

The index, middle, ring and little fingers are segmented into three parts. The segments are referred to as the proximal phalanx, medial phalanx and distal phalanx depending on their proximity to the palm (Figure 2-1). The thumb has two segments: the proximal phalanx and the distal phalanx.

2.2.1 Location of blood vessels in the finger and palm

The blood vessels in the hand are part of a network of connected blood vessels called the cardiovascular system. The cardiovascular system has two parts: the arterial system and the venous system. The arterial system feeds blood to the hand. The venous system returns the blood from

the hand to the heart.

2.2.1.1 Arterial system

The blood flow to the hand is fed by the radial and ulnar arteries. Figure 2-2 shows the location of arteries in the palm and digits. The radial and ulnar arteries link in the palm to form the deep palmar arch and the superficial palmar arch. The deep palmar arch leads into the palmar metacarpal arteries. From the superficial palmar arch stem the common palmar digital arteries which in turn branch in each finger to form two proper palmar digital arteries in each of the fingers. In each finger the common digital arteries branch to feed the dorsum of the middle and distal phalanges. The thumb arteries come from the deep palmar arch.

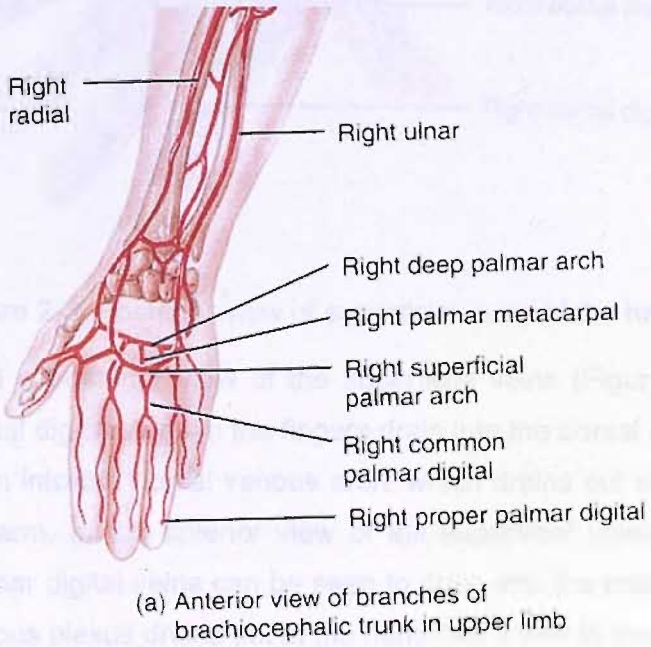


Figure 2-2 Arteries in the palm and finger (Marieb, 2003)

The digital arteries branch into many smaller arterioles, and then into capillaries. The capillaries are the blood vessels with the smallest diameter. Capillaries form interweaving networks called capillary beds containing true capillaries. The true capillaries number 10 to 100 per bed.

2.2.1.2 Venous system

Figure 2-3, Figure 2-4 and Figure 2-5 show the three networks of veins in the palm and digits that drain blood from the hand. There are two networks of superficial veins and one network of deep veins.

The superficial veins are some of the larger veins in the hand and are located just below the skin. Superficial veins anastomose extensively with one another and with deep veins. The superficial veins and the deep veins return most of the blood from the hand to the upper limbs.

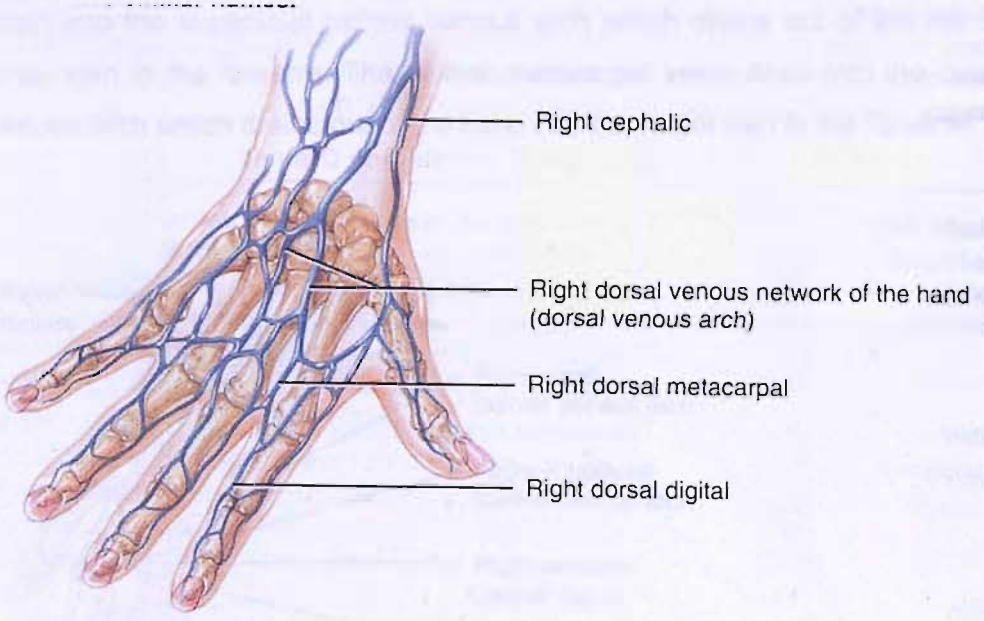


Figure 2-3 Posterior view of superficial veins of the hand (Marieb, 2003)

With a posterior view of the superficial veins (Figure 2-3) it can be seen that the dorsal digital veins in the fingers drain into the dorsal metacarpal veins. These in turn drain into the dorsal venous arch, which drains out of the hand into the veins in the forearm. In the anterior view of the superficial veins in the hand (Figure 2-4), the palmar digital veins can be seen to drain into the palmar venous plexus. The palmar venous plexus drains out of the hand into a vein in the forearm.

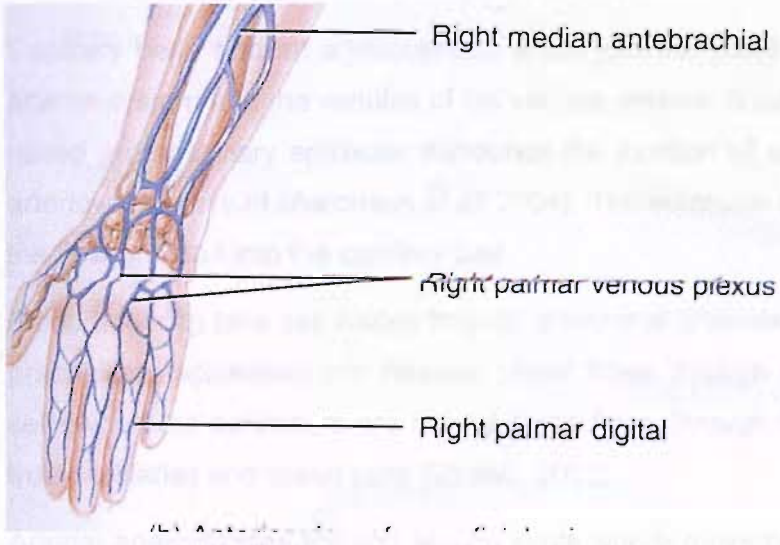


Figure 2-4 Anterior view of superficial veins in the hand (Marieb, 2003)

Deep veins are heavily valved to ensure unidirectional blood flow to the heart and to prevent blood from flowing back into the hand. Figure 2-5 shows the deep veins within the hand.

The proper palmar digital veins drain into the common palmar digital veins. These drain into the superficial palmar venous arch which drains out of the hand into the ulnar vein in the forearm. The palmar metacarpal veins drain into the deep palmar venous arch which drains out of the hand into the radial vein in the forearm.

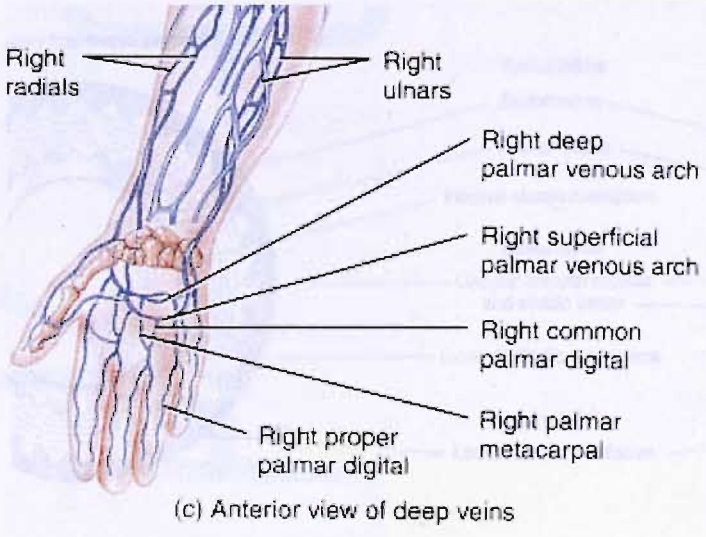


Figure 2-5 Anterior view of deep veins of the hand (Marieb, 2003)

The digital veins branch to form smaller diameter vessels called venules, which also branch to form capillaries.

2.2.2 Linking the arterial and venous systems

Capillary beds and an arteriovenous shunt join the small terminal arterioles of the arterial system and the venules of the venous system. A cuff of smooth muscle fibres called a precapillary sphincter surrounds the junction of each capillary bed and the arteriovenous shunt (Aaronson *et al*, 2004). The sphincter acts as a valve to regulate the flow of blood into the capillary bed.

Blood flow can take two routes through a terminal arteriole to the venules. When the precapillary sphincters are relaxed, blood flows through the capillaries and tissue cells;when the sphincters are closed blood flows through the shunts, bypassing the true capillaries and tissue cells (Marieb, 2003).

Arterial anastomoses abound around joints where movement may hinder blood flow

through one channel. The fingers contain a number of arteriovenous anastomoses, most numerous in the tips of the fingers, nail bed and palmar surface of the digits. Arterial anastomoses are important in regulating finger temperature (Marieb, 2003).

2.2.3 Tissue structure in the arteries and veins

2.2.3.1 Tissue structure in arteries

The arteries in the hand and digits are muscular arteries. Figure 2-6 shows the three

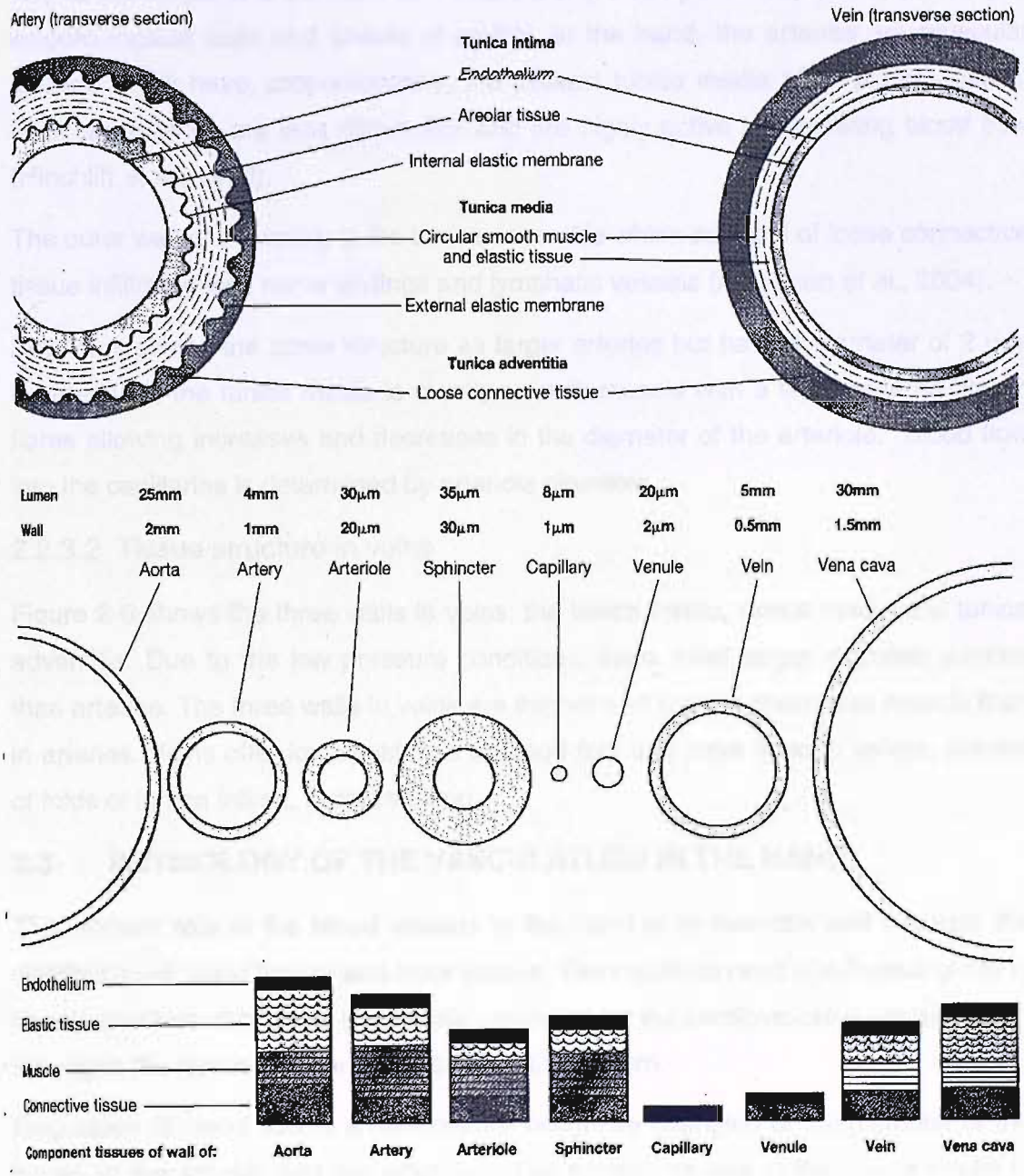


Figure 2-6 Structure of arteries and veins (Hinchliff *et al.*, 1996)

walls in muscular arteries: the tunica intima, tunica media and tunica adventitia.

The tunica intima is the innermost wall and consists of areolar tissue and the endothelium, a lining of flattened epithelium cells (Aaronson *et al.*, 2004). The endothelium contains the nerve endings that respond to various stimuli acting at the skin surface (pressure, heat, etc.). The endothelium accomplishes many functions, including providing a friction-reducing lining for blood flow, protecting underlying tissues from mechanical, chemical and bacterial injury and encouraging the efficient exchange of nutrients (Hinchliff *et al.*, 1996).

The tunica media is the middle wall of the artery and consists of circularly arranged smooth muscle cells and sheets of elastin. In the hand, the arteries are muscular arteries which have, proportionately, the thickest tunica media of all blood vessels. Muscular arteries are less distensible and are highly active in regulating blood flow (Hinchliff *et al.*, 1996).

The outer wall of the artery is the tunica adventitia which consists of loose connective tissue infiltrated with nerve endings and lymphatic vessels (Aaronson *et al.*, 2004).

Arterioles exhibit the same structure as larger arteries but have a diameter of 2 μm. In arterioles, the tunica media is mostly smooth muscle with a few scattered elastic fibres allowing increases and decreases in the diameter of the arteriole. Blood flow into the capillaries is determined by arteriole diameter.

2.2.3.2 Tissue structure in veins

Figure 2-6 shows the three walls in veins: the tunica intima, tunica media and tunica adventitia. Due to the low pressure conditions, veins have larger diameter lumens than arteries. The three walls in veins are thinner and contain much less muscle than in arteries. Veins offer low resistance to blood flow and have venous valves, formed of folds of lumen intima, to move blood.

2.3 PHYSIOLOGY OF THE VASCULATURE IN THE HAND

The primary role of the blood vessels in the hand is to maintain and regulate the distribution of blood flow to and from tissues. The regulation and distribution of blood flow to and from the hands is primarily controlled by the cardiovascular system which manages the needs of other vessels within the system.

Regulation of blood flow to a blood vessel occurs by changing of the diameter of the lumen of the arteries and the arterioles. The smooth muscle in the tunica media is constantly in a state of active tension (vascular tone). Resistance and blood velocity in a blood vessel are sensed and controlled in order to regulate blood flow as

required. A reduction in blood flow through a vessel occurs when the smooth muscle contracts and the diameter of the vessel lumen gets smaller (vasoconstriction). During contraction while blood flow is low the arterial resistance in the blood vessel and the blood velocity are high.

Blood flow in a vessel increases when the tension of the smooth muscle is relaxed and the diameter of the vessel lumen increases (vasodilation). During relaxation, while the flow of blood volume is high, the arterial resistance in the blood vessel and blood velocity is low.

Complete occlusion of the vessels will compromise the viability of the tissue. Lesser degrees of disturbed flow will effect the local intravascular environment to which the vessel wall will respond.

The secondary role of the blood vessels in the hand is to regulate body temperature.

2.3.1 Physiology of smooth muscle contraction

The concentration of calcium ions (Ca^{2+}) in the cells of arterial smooth muscle primarily defines the degree of contraction or relaxation occurring in the smooth muscle. High levels of calcium ions cause contraction and low levels of calcium ions cause relaxation. Calcium ions can originate in the extracellular space around the smooth muscle cell and in the sarcoplasmic reticulum (cytoplasm) within the cell (Aaronson *et al.*, 2004).

The influx or release of calcium ions in vascular smooth muscle occurs by neural and hormonal contractile stimulants acting on, or in, the cells.

Calcium ions originating in the extracellular space enter the cell via ligand-gated calcium channels and voltage-gated calcium channels. Ligand-gated calcium channels are hormone activated. Voltage-gated calcium ion channels are activated by neurally-controlled membrane deplorisation. Once activated, calcium channels release calcium ions into the cytoplasm.

The calcium ions in the cytoplasm of the smooth muscle cell bind to calmodulin, a calcium binding protein. The calcium-calmodulin complex activates an enzyme called myosin light-chain kinase, which phophorylates, permitting the myosin light-chain kinase to bind to actin. Actin and myosin interact by filament sliding to produce contraction of the smooth muscle and a reduction in the diameter of the blood vessel. Relaxation of the smooth muscle and an increase in the diameter of the blood vessel occurs when the neural or hormonal contractile stimulants cease activating the release of calcium ions.

The activation of ligand-gated calcium channels and the voltage-gated calcium channels in the cell wall is controlled by the endocrine system or sympathetic nervous system, respectively.

2.4 VIBRATION SENSATION

Vibration of the hand is detected by sensory mechanoreceptors distributed within the skin of the hand. Different mechanoreceptors respond to different frequencies of vibration. Pacinian corpuscles respond to high frequency vibration and are most sensitive at approximately 125 Hz (Lindsell and Griffin, 1998). Meissner corpuscles respond to lower frequency vibration and are more sensitive than Pacinian corpuscles at frequencies less than about 31.5 Hz vibration (Lindsell and Griffin, 1998).

The sensory information detected by the mechanoreceptors provides information to the central nervous system and can initiate somatic and visceral reflexes.

2.5 CHRONIC VIBRATION EXPOSURE

Long-term exposure to hand-transmitted vibration can result in the signs and symptoms of the hand-arm vibration syndrome (HAVS). The study of the acute effects of hand-transmitted vibration may provide an understanding of how the body reacts to vibration. The study of the chronic effects of exposure to hand-transmitted vibration may indicate where and how damage occurs in the body. The mechanisms involved in the development of HAVS are not yet understood.

2.5.1 Signs, symptoms and diagnosis of chronic vibration exposure

Hand-arm vibration syndrome has vascular, sensori-neural and musculo-skeletal components. Although this thesis concentrates on the vascular component of HAVS, the signs and symptoms and methods of diagnosis for all components of HAVS are described.

The principal vascular component of HAVS is vibration-induced white finger (VWF), characterised by attacks of blanching resulting from reduced digital blood flow during and after exposure to cold. Blanching is pallor or whiteness of the digits and is clearly demarcated from the normal colouration of the skin. Typically blanching first affects the tip of one or more digits. As the disorder progresses the blanching extends to the medial and proximal phalanges of the affected digits (HS(G) 88, HSE Books). The thumb may also be affected by blanching. The distribution of whiteness has been reported to be related to the distribution of vibration exposure to the hand. Taylor and Pelmear (1975) state that the digits most exposed to vibration are usually

the first to blanch. The return of circulation can be accompanied by throbbing and redness in the affected digits.

Two standardised tests have been recommended for the assessment of vascular function in a person who has symptoms of VWF (The Control of Vibration at Work Regulations (L140), 2005). The measurement of finger skin temperature following cold provocation is widely used to detect the abnormal cold response associated with VWF (Lindsell and Griffin, 2001). A prolonged re-warming time following immersion of a hand in cold water, compared to the response of subjects without vascular dysfunction, indicates an abnormal response to cold (Welsh, 1983, 1986). .

Measures of finger systolic blood pressure following local cooling also indicate the response of a digital artery to changes in temperature. The dysfunction causing VWF is associated with greater reductions in finger systolic blood pressures (FSBPs) following cold provocation compared with reductions in normal healthy individuals (Lindsell and Griffin, 1998).

Blanching is not often seen during standardised cold provocation testing. A verbal description of blanching is recorded on a 'blanching map'. The distribution of vascular dysfunction measured using one or both of the standardised tests can be compared with the distribution of blanching on the blanching map to assess the consistency of the signs and symptoms.

The sensori-neural symptoms linked with HAVS include tingling and numbness in the affected digits due to damage to nerves in the hand (The Control of Vibration at Work Regulations (L140), 2005). Standardised tests for the assessment of sensori-neural dysfunction include a measure of thermal thresholds and a measure of vibrotactile thresholds. The thermal thresholds provide a measure of the function of the thermal sensory system. The vibrotactile thresholds provide a measure of the function of the mechanoreceptors in the hand. The sensorineural dysfunction associated with HAVS is associated with elevated thermal and vibrotactile thresholds in the affected digits.

The vascular and sensori-neural signs and symptoms can be graded using the Stockholm Workshop Scale (Gemne *et al.*, 1987). The presentation of signs and symptoms must be accompanied by a history of significant exposure to hand-transmitted vibration for a diagnosis of HAVS to be made (Griffin and Bovenzi, 2002).

The third set of symptoms associated with HAVS are joint pain, stiffness in the hand and arm (The Control of Vibration at Work Regulations (L140), 2005). Reduced manual dexterity and grip strength are indicators of musculoskeletal dysfunction.

2.5.2 Epidemiological studies

Several epidemiological studies have been conducted in an attempt to determine exposure-response relationships between hand-transmitted vibration and HAVS, in particular the vascular disorder VWF.

The prevalence and severity of VWF symptoms have been considered dependent on the frequency and magnitude of hand-transmitted vibration and various measures of the exposure duration (hours in the day or years of exposure) in epidemiological studies.

The prevalence of exposure to hand-transmitted vibration in Great Britain in a 1 week period has been estimated at 4.2 million men and 667,000 women (Palmer *et al.*, 2000). The industries that contributed 49% of the total of exposed men were (largest to smallest number of workers): construction, motor vehicle maintenance and repair, manufacture of fabricated metal products other than machinery and equipment, and defence. The occupations that contributed the greatest number of exposed women were (largest to smallest number of workers): cleaner or domestic worker and hairdresser.

A vibration exposure history should include identification of the tools used and the frequency of use. Palmer *et al.* (2000) report that the most common vibratory tools that men were exposed to were the hammer drill (1.7 million users nationwide), the hand held portable grinder (1.5 million users nationwide) and the jig saw (1.0 million users nationwide. The most common vibratory tools used by women were floor polishers. An understanding of the tools used can indicate which frequencies, magnitudes and what durations of exposure can lead to VWF symptoms and signs.

Epidemiological studies suggest that the prevalence of VWF in the workforce is not only related to the vibration exposure but also to the geographical location and climate, and gender. The prevalence of VWF ranges from 0 to 5% in workers using vibratory tools in warm climates and 80 to 100% in workers in northern cooler climates (Bovenzi, 1998).

Attempting to relate a vibration exposure history to symptoms can be subject to problems as many factors can affect the accurate representation of a vibration history. Individuals can overestimate and underestimate the exposure durations depending on their job security, financial gains, and other psycho-social factors. The use of anti-vibration gloves or tools and a health surveillance program may influence the vibration impact. Poor tool maintenance, training and inappropriate use of tools can increase the vibration dose compared to manufacturer's guidelines. The contact

locations, push force, grip force, arm position, temperature of the working environment and other operational factors may affect the dose of vibration (Griffin, 1990). Lastly, the individual susceptibility to vibration varies considerably between workers (Gerhardsson *et al.*, 2005).

The progression of dysfunction associated with VWF may depend on whether vibration exposure is continued, reduced, or ceased. In a follow-up study involving claimants seeking compensation for VWF dysfunction, Bovenzi *et al.* (2005) reported that deterioration of the cold response of the arteries was firstly associated with VWF symptoms and secondly associated with the duration of vibration exposure since the initial assessment. The cold response of the arteries was assessed by measuring finger systolic blood pressure. There is clinical and epidemiological evidence that symptoms and signs of VWF may be reversible after the reduction or cessation of vibration exposure (Bovenzi, 1998). The reversibility may be related to the severity of the symptoms at the time vibration exposure ceased and the worker's age (Bovenzi, 1998).

2.6 EFFECT OF ACUTE VIBRATION EXPOSURE ON PERIPHERAL VASCULAR ACTIVITY

Although the chronic and acute effects of vibration exposure may differ, the study of the acute effects of vibration may provide an understanding of how the body reacts to long-term exposures to vibration.

In an attempt to understand the relationship between vibration characteristics and VWF, a few previous studies have exposed people with VWF to vibration in the laboratory. Other studies have exposed healthy subjects, with no prior vibration exposure, to vibration. The normal response to vibration may indicate the characteristics of the vibration to which the body is sensitive.

2.6.1 Measurement of finger blood flow

In the fingers, four aspects of vascular activity are commonly measured: finger skin temperature, finger systolic blood pressure, cutaneous blood flow, and arterial blood flow.

Finger skin temperature (FST) measures the surface temperature of the skin. Finger skin temperature provides a superficial picture of blood flow in the hand and is easy to measure. However, finger skin temperature is prone to measurement artefacts from external environmental conditions and only indicates blood flow in the skin, rather than within the digit. In research settings, the measurement of FST is still used

as a quick and convenient indicator of vascular activity in conjunction with other tests. For diagnostic testing of vascular function, finger skin temperature is measured before, during and after cold provocation in order to calculate the finger re-warming time.

Finger systolic blood pressure (FSBP) is used to measure the effect of finger temperature on blood pressure in the digit. A decrease in finger systolic blood pressure indicates reduced circulation, and zero pressure shows that there is arterial closure. The measurement of FSBP involves suprasystolic occlusion pressures. The cold temperatures used in the measurement of FSBP can be painful.

Finger blood flow is a sensitive measure of arterial flow. Digital blood flow can be measured using laser Doppler or venous occlusion plethysmography.

Laser Doppler methods provide non-invasive measures of blood velocity. The system utilizes the Doppler shift of laser light backscattered from moving red blood cells in the cutaneous microcirculation. Laser Doppler methods allow continuous measurement of blood flow. A disadvantage of the laser Doppler method is that measurement is limited to the cutaneous blood flow rather than arterial flow within the digit. It is preferable for the hand to be stationary for the duration of a measurement.

The measurement of arterial flow using venous occlusion is non-invasive and has been proved valid (Anderson, 1989). Finger expansion during venous occlusion can be measured using strain gauge plethysmography. A measurement can be made on multiple sites at intervals of one minute or more frequently. The skill required in measuring arterial flow using venous occlusion plethysmography is in the interpretation of the graph showing change in finger circumference over time. Greenfield *et al.* (1963) provide instructions on the interpretation of the recordings of the rate of arterial inflow. There are two conditions underlying the use of venous occlusion plethysmography to measure blood flow. The initial venous occlusion must not impede arterial inflow. The increase in venous pressure during occlusion must not alter arterial inflow (Anderson, 1989). These assumptions must be met for the most accurate measurement of arterial flow.

2.6.2 Acute finger blood flow response to vibration

In some previous experiments the investigation of the acute response to vibration has involved the measurement in healthy subjects of finger blood flow (FBF) before vibration exposure and after vibration exposure. In more recent studies, finger blood flow has been measured before, during, and after vibration exposure. Figure 2-7 shows a typical finger blood flow response before, during, and after vibration.

In order to show the dependence of blood flow on the vibration exposure, the blood flow during vibration exposure and after vibration has been compared to the finger blood flow during a 'pre-exposure' period before vibration.

A change in blood flow during and after vibration can be shown as a percentage of the pre-exposure finger blood flow measurement (e.g. 30% of the pre-exposure finger blood flow was a reduction of 70% of pre-exposure finger blood flow).

Figure 2-7 shows that vibration has typically caused a reduction in finger blood flow during vibration exposure. After the end of vibration, vasodilation occurred and caused a return in blood flow to pre-exposure blood flow levels. A delayed vasoconstriction is shown some time after vibration exposure in Figure 2-7.

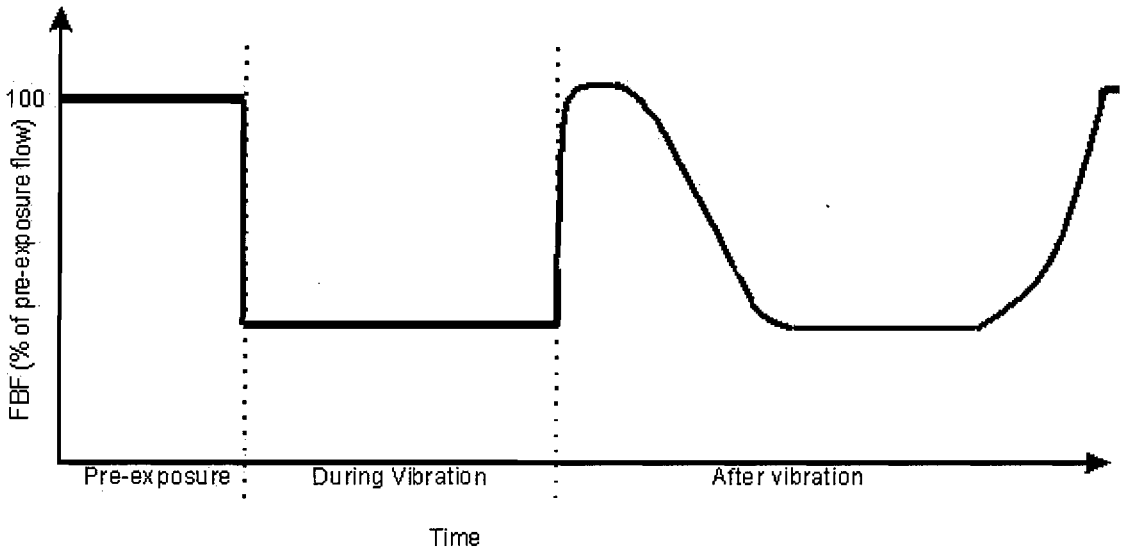


Figure 2-7 Typical response of finger blood flow before, during and after vibration exposure as described in previous studies in the literature review.

Experimental studies have tested the dependence of finger blood flow on the frequency, magnitude, duration, and direction of acute vibration exposure (see below).

Finger blood flow was generally measured in the hand exposed to vibration (exposed hand). In some studies, finger blood flow has been measured in the hand not exposed to vibration (contralateral unexposed hand) and in a digit not exposed to vibration but on the exposed hand (unexposed ipsilateral digit).

2.6.3 Stimulus frequency

2.6.3.1 During vibration

With a constant amplitude of vibration, Welsh (1980, 1983) found a greater reduction in finger blood flow in the exposed hand during vibration at 120 Hz, compared to during exposure at 40, 80, 160 and 200 Hz (Figure 2-8). At 120 Hz Welsh (1980) reported a range of 60 to 80 percent reduction in blood flow. Figure 2-8 shows that the strength of the vasoconstriction varied according to the frequency of vibration.

With acceleration magnitudes of 10 and 50 ms^{-2} r.m.s., Furuta *et al.* (1991) reported a more pronounced vasoconstriction in the exposed finger at frequencies of 31.5, 63, 250 and 500 Hz than at 16, 125 and 1000 Hz. Furuta *et al.* (1991) state that vibration at 31.5 to 63 and 500 Hz caused reductions of 50 percent or more compared to pre-exposure blood flow. The frequencies considered by Welsh (1980) and Furuta *et al.*, (1991) to be most vasoactive are different.

Furuta *et al.* (1991) reported a similar frequency-dependency of blood flow in the exposed and unexposed hand, but with less vasoconstriction on the unexposed hand. A similar frequency-dependent reduction in blood flow in the exposed and unexposed hand may indicate a centrally mediated response to hand-transmitted

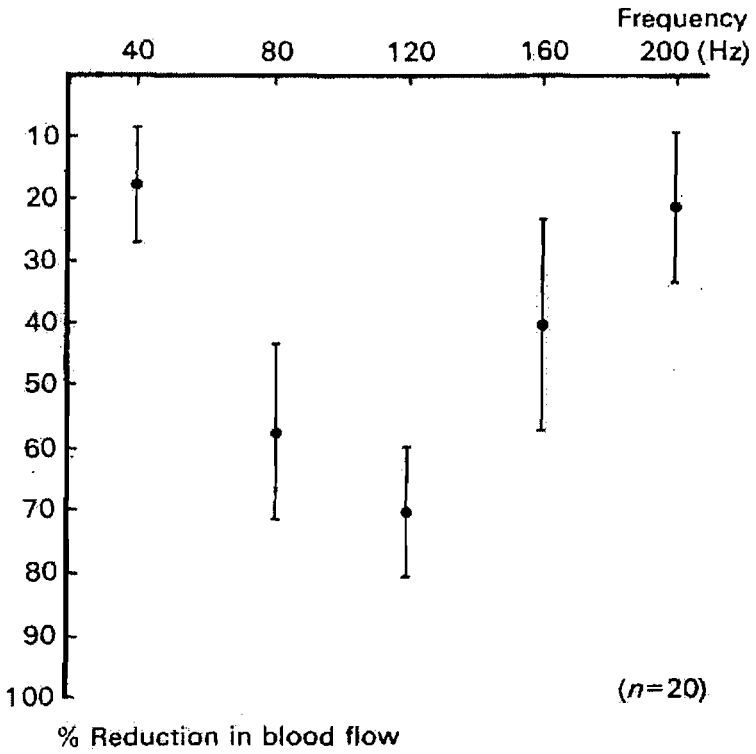


Figure 2-8 An effect on digital blood flow in the exposed hand of increasing vibration frequency at a constant amplitude of 0.5 mm with 20 healthy subjects (Welsh, 1980).

vibration.

Bovenzi *et al.* (2000) found that finger blood flow in the exposed hand was strongly reduced during exposure to vibration with the same velocity at frequencies between 31.5 and 250 Hz, but only slightly reduced during exposure to 16 Hz vibration. Figure 2-9 shows the effects of vibration frequency on the maximum reduction of finger blood flow (percentage of values before exposure) during and after vibration exposure at frequencies in the range of 16 to 250 Hz with different combinations of frequencies and unweighted acceleration magnitudes, but with the same frequency-weighted acceleration of 5.5 ms^{-2} r.m.s. The stimuli have the same vibration velocity.

Similar to Furuta *et al.* (1991), Bovenzi *et al.* (2000) found a dependency of finger blood flow on vibration frequency when using vibrations with the same velocity. Bovenzi *et al.* (2000) report that in the unexposed hand there were more pronounced reductions in finger blood flow at higher vibration frequencies than at lower frequencies during vibration exposure (Figure 2-9).

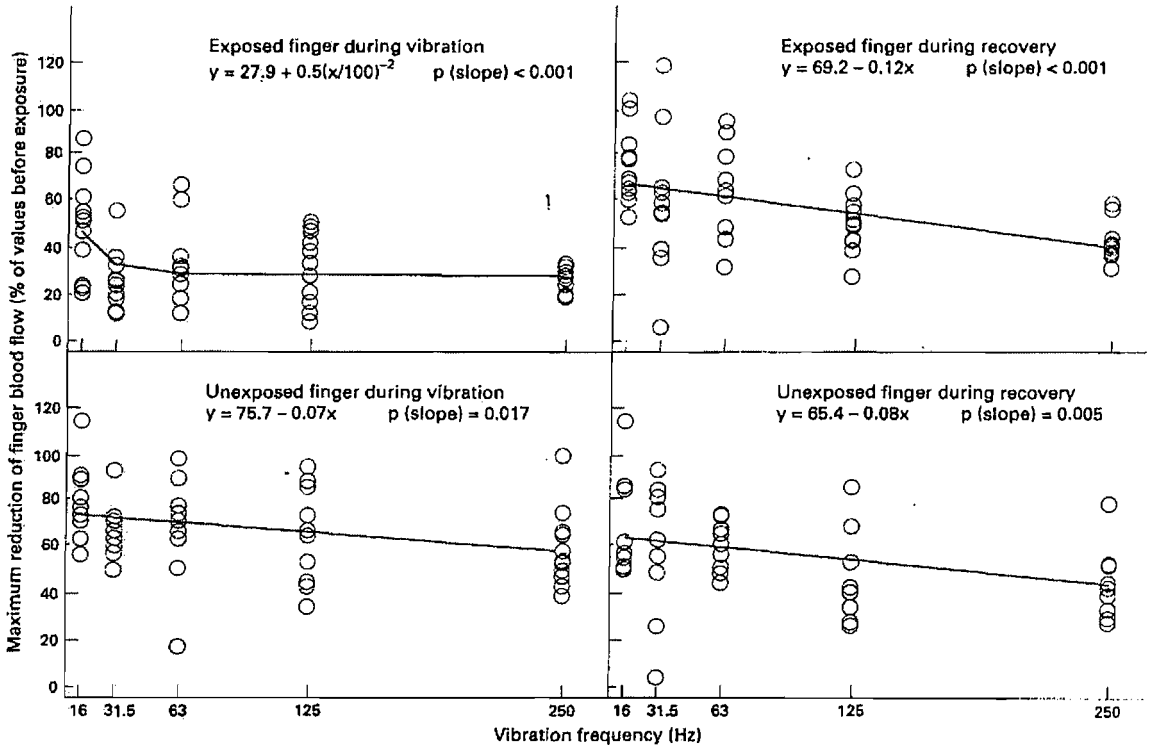


Figure 2-9 Effects of vibration frequency on the maximum reduction of finger blood flow during and after vibration exposure at frequencies in the range of 16 to 250 Hz vibration with different combinations of frequencies and unweighted acceleration magnitudes but with the same frequency-weighted acceleration (5.5 ms^{-2} r.m.s.) (Bovenzi *et al.*, 2000).

Furuta *et al.* (1991) and Bovenzi *et al.* (2000) found that at all vibration frequencies the vasoconstriction in the exposed hand was greater than the vasoconstriction in the unexposed hand. Figure 2-10 shows the mean values of finger blood flow measured in ten healthy men before, during, and after 15-minutes exposure to static load (contact force 10 N) or vibration with different combinations of frequencies and unweighted acceleration magnitudes but with the same frequency-weighted acceleration of 5.5 ms^{-2} r.m.s.

2.6.3.2 After vibration

Nohara *et al.* (1986) reported vasoconstriction following the end of vibration exposure. The vasoconstriction was stronger following exposure at 60 and 480 Hz than following vibration at 30, 120, 240 and 960 Hz when the vibration magnitude was 50 ms^{-2} r.m.s. at all frequencies (Figure 2-11).

Bovenzi and Griffin (1997) found a dependency of finger blood flow in the exposed hand on vibration frequency 20, 40 and 60-minutes after vibration at 31.5 and 125 Hz with a constant acceleration of 22 ms^{-2} r.m.s. A reduction in finger blood flow was found in fingers on the exposed and unexposed hands. On the exposed hand,

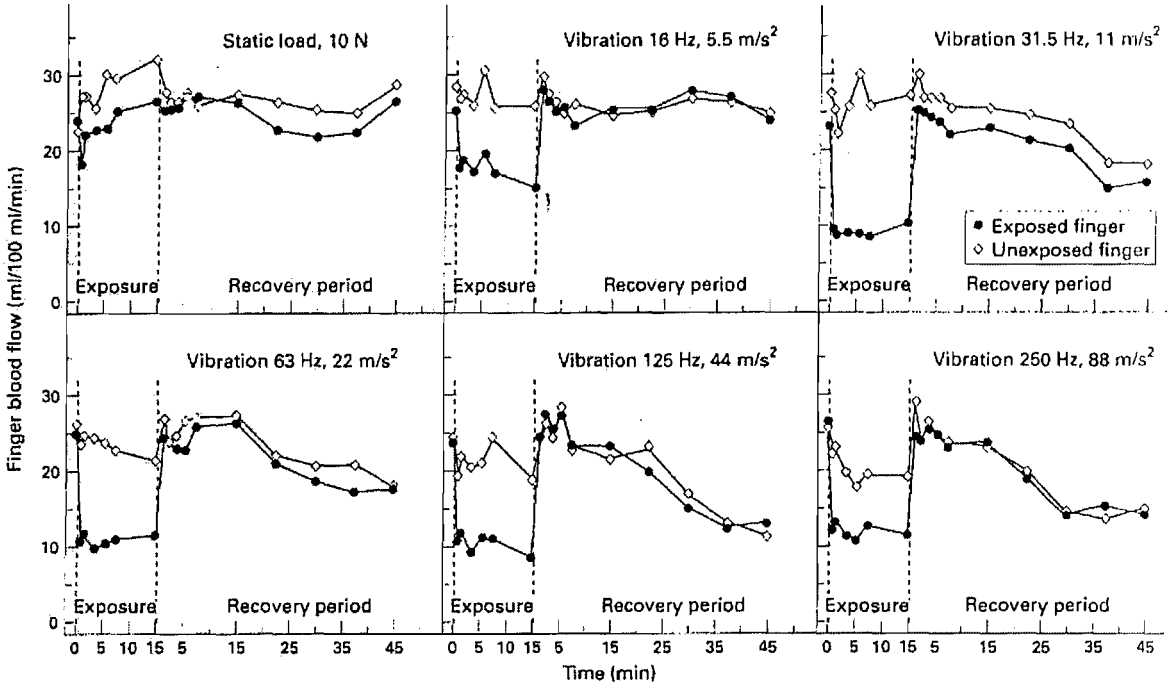


Figure 2-10 Mean values of finger blood flow measured in 10 healthy men before, during and after 15-minutes of exposure to static load (contact force 10 N) or vibration with different combinations of frequencies (Hz) and unweighted acceleration magnitudes but with the same frequency-weighted acceleration (5.5 ms^{-2} r.m.s.) (Bovenzi *et al.*, 2000).

vasoconstriction was stronger after vibration at 125 Hz than after vibration at 31.5 Hz. Although a finger on the unexposed hand showed a reduction in blood flow after vibration, there was no significant difference in the vasoconstriction after vibration at 125 Hz or 31.5 Hz.

After the end of vibration, Bovenzi *et al.* (2000) found an initial immediate increase in finger blood flow in the exposed hand that was independent of the vibration frequency (Figure 2-10).

Other studies have reported a vasodilation in the exposed hand immediately after the end of exposure at 125 Hz (Bovenzi and Griffin, 1997; Bovenzi *et al.*, 1998, 1999; 2001). Although a vasodilation was reported by Bovenzi and Griffin (1997) immediately following vibration at 125 Hz and an acceleration of 87 ms^{-2} r.m.s., no vasodilation was found at the same frequency and a lower magnitude of 22 ms^{-2} r.m.s. Bovenzi *et al.* (1998, 1999 and 2001) only exposed subjects to vibration at 125 Hz, so no comparisons can be made with other frequencies of vibration.

After the initial vasodilation in the exposed digit, Bovenzi *et al.* (2000) reported a delayed reduction in finger blood flow in the exposed and unexposed hand. In both hands, the greater the frequency of vibration the stronger was the reduction in finger

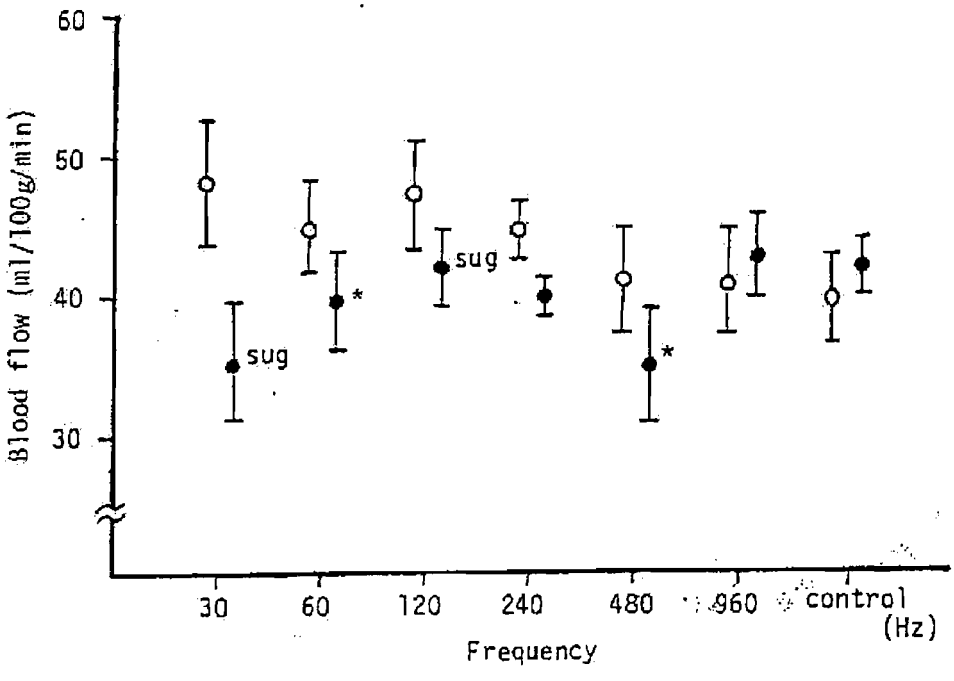


Figure 2-11 Effect of various frequencies on finger blood flow on hands exposed for 1 hour to local vibration at 50 ms^{-2} r.m.s. Each circle with a vertical line represents the mean and standard error of the mean of five healthy men. White circles indicate finger blood flow before vibration exposure; black circles indicate finger blood flow after vibration exposure (Nohara, 1986).

blood flow after vibration (in the range 16 to 250 Hz after exposure to a frequency-weighted acceleration of 5.5 ms^{-2} r.m.s.).

2.6.3.3 Conclusion

It is not yet clear which frequencies produce the greatest reduction in finger blood flow in the exposed or contralateral hand during or after vibration exposure.

2.6.4 Stimulus magnitude

2.6.4.1 During vibration

Increased reduction in finger blood flow in the exposed finger has been reported with increasing vibration displacement from 0.125 to 1.00 mm at a frequency of 80 Hz (Welsh, 1980). Figure 2-11 shows the effect on finger blood flow of increasing the vibration displacement at a constant frequency in the exposed hand (Welsh, 1980).

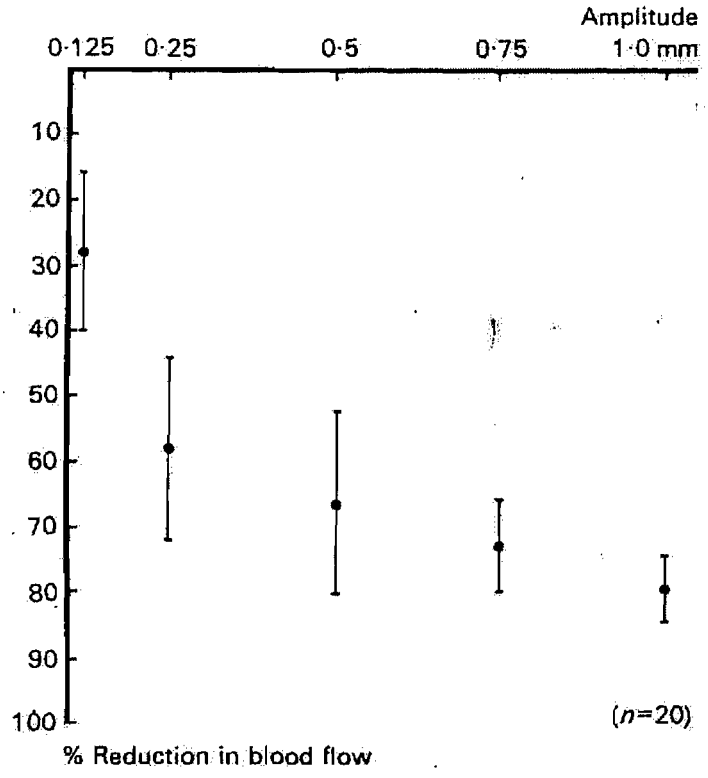


Figure 2-11 An effect on digital blood flow in the exposed hand of increasing amplitude with a constant frequency of 80 Hz (Welsh, 1980).

Egan *et al.* (1996) found greater reduction in finger blood flow in the exposed and contralateral finger during exposure to high intensity than low intensity vibration across a broadband frequency range of 0.4 to 4000 Hz via a chisel.

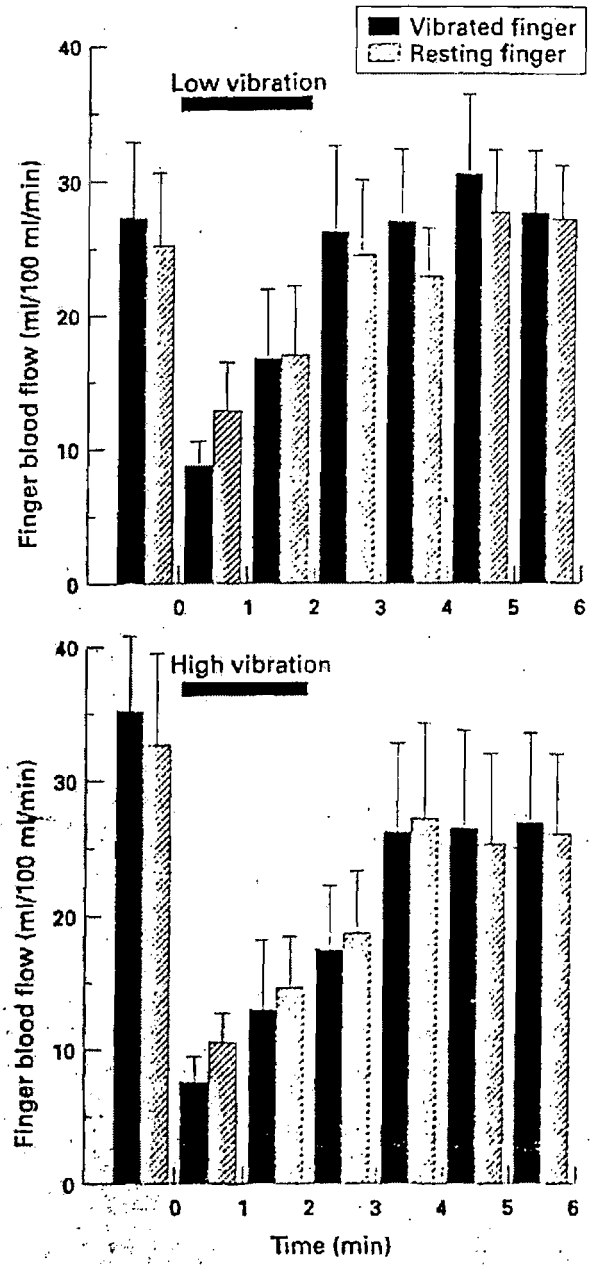


Figure 2-12 Mean (SEM) middle finger blood flow in the vibrated and unexposed hands of 12 healthy subjects before, during and after two minutes of vibration. The upper graph shows the effect of low intensity vibration on finger blood flow and the lower graph shows the effect of high intensity vibration on finger blood flow (Egan *et al.*, 1996)

Figure 2-12 shows the mean (SEM) middle finger blood flow in the vibrated and unexposed hands of 12 healthy subjects before, during, and after two minutes of vibration. The upper graph shows the effect of low intensity vibration on finger blood flow and the lower graph shows the effect of high intensity vibration on finger blood flow. Low intensity of vibration was produced by an air flow of 65 l/min through a chisel. High intensity vibration was produced by air flow of 75 l/min through the chisel. Low and high intensity vibration caused reductions in finger blood flow in the exposed and the unexposed hands for the duration of the vibration exposure. A stronger reduction in finger blood flow was reported in the exposed hand than in the unexposed hand during the first minute of vibration exposure at both intensities of vibration. From Figure 2-12 it appears that the strength of the vasoconstriction was similar at a low or high intensity of vibration.

Although using a broadband of vibration frequencies, Egan *et al.* (1996) state that the reduction in finger blood flow during exposure to vibration in their study was of a similar magnitude to that reported by Welsh (1980) who used sinusoidal vibration.

Bovenzi *et al.* (1999) measured finger blood flow during vibration with increasing vibration acceleration magnitude. Figure 2-13 shows the percentage reduction in finger blood flow in the exposed finger during vibration compared to finger blood flow before vibration exposure. Increased reductions in blood flow were reported with increasing acceleration magnitude. Compared to pre-exposure blood flow, the reduction in blood flow with 125 Hz vibration at 5.5, 22, 44 and 62 ms^{-2} r.m.s. was 55, 44, 35 and 20 percent of pre-exposure finger blood flow, respectively. The unexposed finger showed the same trend but to a lesser degree during vibration, with reductions in flow at 22, 44, and 62 ms^{-2} r.m.s. of 70, 60 and 60 percent of pre-exposure flow, respectively. The dependence of finger blood flow on vibration magnitude is consistent with the findings of Welsh (1980) and the corresponding response in the unexposed hand are consistent with the findings of Egan *et al.* (1996)

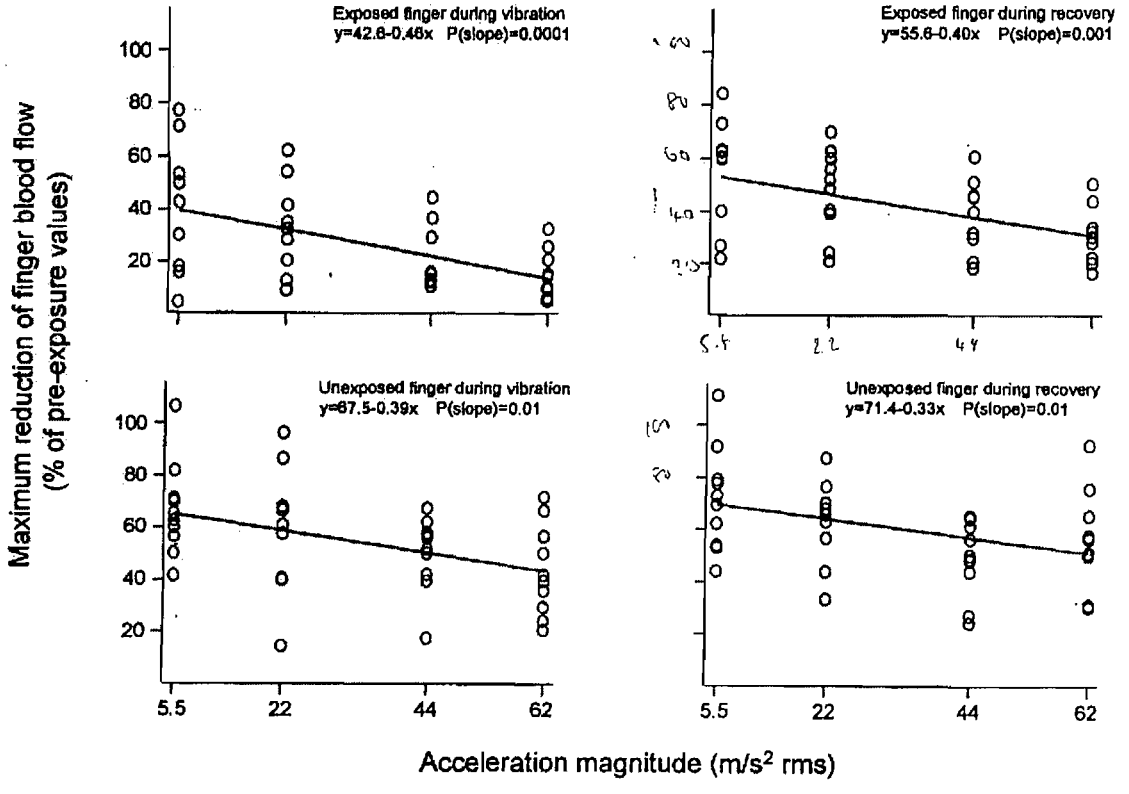


Figure 2-13 The percentage reduction in finger blood flow from pre-exposure levels in the exposed hand during and after exposure to vibration of different magnitudes (Bovenzi *et al.*, 1999).

The findings of Luo *et al.* (2000) seem consistent with previous studies reporting that a higher acceleration magnitude of vibration (31.6 m s^{-2} r.m.s.) tended to produce a greater decrease in finger blood flow in the exposed and unexposed hands than exposure to vibration with an acceleration magnitude of 3.16 ms^{-2} r.m.s. at 60 Hz. As with previous studies, Luo *et al.* (2000) report that the unexposed left hand showed a similar, but lesser, blood flow response to the exposed hand.

2.6.4.2 After vibration

Immediately following vibration exposure of various magnitudes (0.125 to 0.5 mm) at various frequencies of vibration (40 to 200 Hz) Welsh (1980) reported an increase in finger blood flow.

Egan *et al.* (1996) found that after the end of exposure to low intensity vibration of the whole hand over the frequency range 0.4 to 4000 Hz, finger blood flow in the exposed and unexposed hand increased compared to finger blood flow during vibration exposure. The vasodilation in the exposed and unexposed hand is shown between minute 3 and minute 6 in Figure 2-12. In contrast, Egan *et al.* (1996) report that at the end of exposure to high intensity vibration, finger blood flow was reduced compared to blood flow before vibration exposure. The difference in response between blood flow after low and high intensity vibration is confounded by a marked difference in finger blood flow before exposure to high intensity vibration than before exposure to low intensity vibration (Figure 2-12). Egan *et al.* (1996) report that ten to twenty minutes after vibration finger blood flow in both hands had significantly reduced compared to pre-exposure blood flow.

Bovenzi and Griffin (1997) report that immediately following exposure to vibration, acceleration of 87 ms^{-2} r.m.s. at 125 Hz there was a significant increase in finger blood flow in the exposed hand. In contrast to Egan *et al.* (1996), no increase in blood flow was reported in the unexposed hand with the cessation of vibration. Although Bovenzi and Griffin (1997) report vasodilation following vibration at 125 Hz and 87 ms^{-2} r.m.s., no increase in finger blood flow was found following vibration at 125 Hz with an acceleration magnitude of 22 ms^{-2} r.m.s.

After the initial vasodilation, Bovenzi and Griffin (1997) state that finger blood flow in the exposed and the unexposed hand reduced. There was no difference between finger blood flow after 125-Hz vibration of 22 ms^{-2} r.m.s. and 87 ms^{-2} r.m.s. The similar vasoconstriction in both hands following vibration of different magnitudes is consistent with the findings of Egan *et al.* (1996).

Consistent with earlier studies (Egan *et al.* 1996, Bovenzi and Griffin, 1997), Bovenzi

et al. (1999) reported that the cessation of vibration produced an increase in blood flow in the exposed and unexposed hands. The increase in finger blood flow was similar after vibration at 125 Hz with accelerations of 5.5, 22, 44, and 62 ms^{-2} r.m.s. Figure 2-14 shows the vasodilation occurring immediately after the cessation of vibration.

After an initial vasodilation in the exposed digit, Bovenzi *et al.* (1999) found a greater reduction in finger blood flow after exposure to high vibration magnitudes than after exposure to low vibration magnitudes. Figure 2-8 shows the percentage reduction in blood flow after vibration compared to finger blood flow before vibration exposure. Compared to pre-exposure blood flow the reduction in blood flow at 22, 44 and 62 ms^{-2} r.m.s. was 60, 50, and 40 percent of pre-exposure flow, respectively.

The unexposed finger showed a lesser reduction in finger blood flow than the exposed finger. Figure 2-14 shows the stronger reduction in finger blood flow in the exposed hand than in the unexposed hand. A significant reduction in finger blood flow in the unexposed hand only occurred after the end of exposure following exposure of the right hand to the higher vibration magnitudes of 44 and 62 m s^{-2} r.m.s.

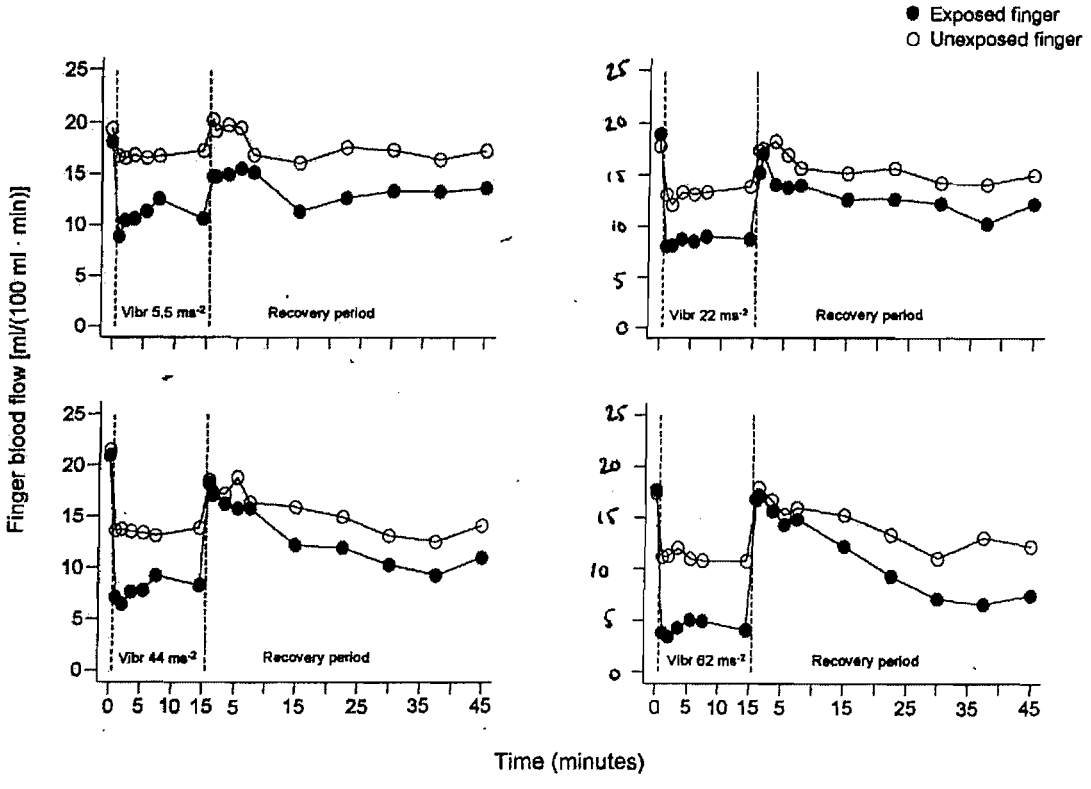


Figure 2-14 Mean values of finger blood flow measured in 10 healthy men before, during and after 15-minute exposure to vibration with a frequency of 125 Hz and acceleration values of 5.5, 22, 44 and 62 ms^{-2} r.m.s. (Bovenzi *et al.*, 1999)

2.6.4.3 Conclusion

A stronger reduction in finger blood flow in the exposed hand and unexposed hand may occur during and after exposure to vibration of high magnitudes than of low magnitudes.

2.6.5 Stimulus duration

2.6.5.1 During vibration

Egan *et al.* (1996) exposed subjects for three 2-minute periods of vibration separated by 10 minute rests. The vibration reduced the finger blood flow in the exposed and unexposed hand by a similar amount during each exposure, although there was a slight downward trend in finger blood flow over the three exposures. Egan *et al.* (1996) explain the similar vascular response during each vibration exposure as resulting from a downward trend in the blood flow during the rest period that affected the calculation of the percentage change of finger blood flow. However, the downward trend was also found in the no-vibration control condition.

Bovenzi *et al.* (1998) found that vasoconstriction in the exposed finger was independent of the duration of 125-Hz vibration exposure for durations of 7.5, 15 and 30 minutes at 87 ms^{-2} r.m.s. Figure 2-15 shows the mean values of finger blood flow in the exposed and unexposed fingers before, during, and after exposure to a static load and vibration of different durations (Bovenzi *et al.*, 1998).

Vasoconstriction occurred in the unexposed hand during the longer vibration exposure durations of 15 and 30 minutes, but not during the shorter exposure durations (Bovenzi *et al.*, 1998) (Figure 2-15). As in previous studies (Egan *et al.*, 1996), the reductions in finger blood flow in the unexposed hand were not as strong as in the exposed hand.

Luo *et al.* (2001) measured finger blood flow over three 5-minute exposure periods separated by 5 minute rests. Consistent with Egan *et al.* (1996), a downward trend in finger blood flow in the unexposed hand over the three periods was reported.

In contrast to Egan *et al.* (1996) and Luo *et al.* (2001), Bovenzi *et al.* (2004) report that intermittent vibration caused a reduction in finger blood flow in the exposed hand similar to that caused by continuous vibration. Intermittent vibration with the same magnitude, frequency, and total exposure duration as a 30-minute continuous vibration were compared. The durations of exposure ranged from one 30-minute duration to 16 periods of 1.88 minutes separated by 1.88 minute periods with no vibration.

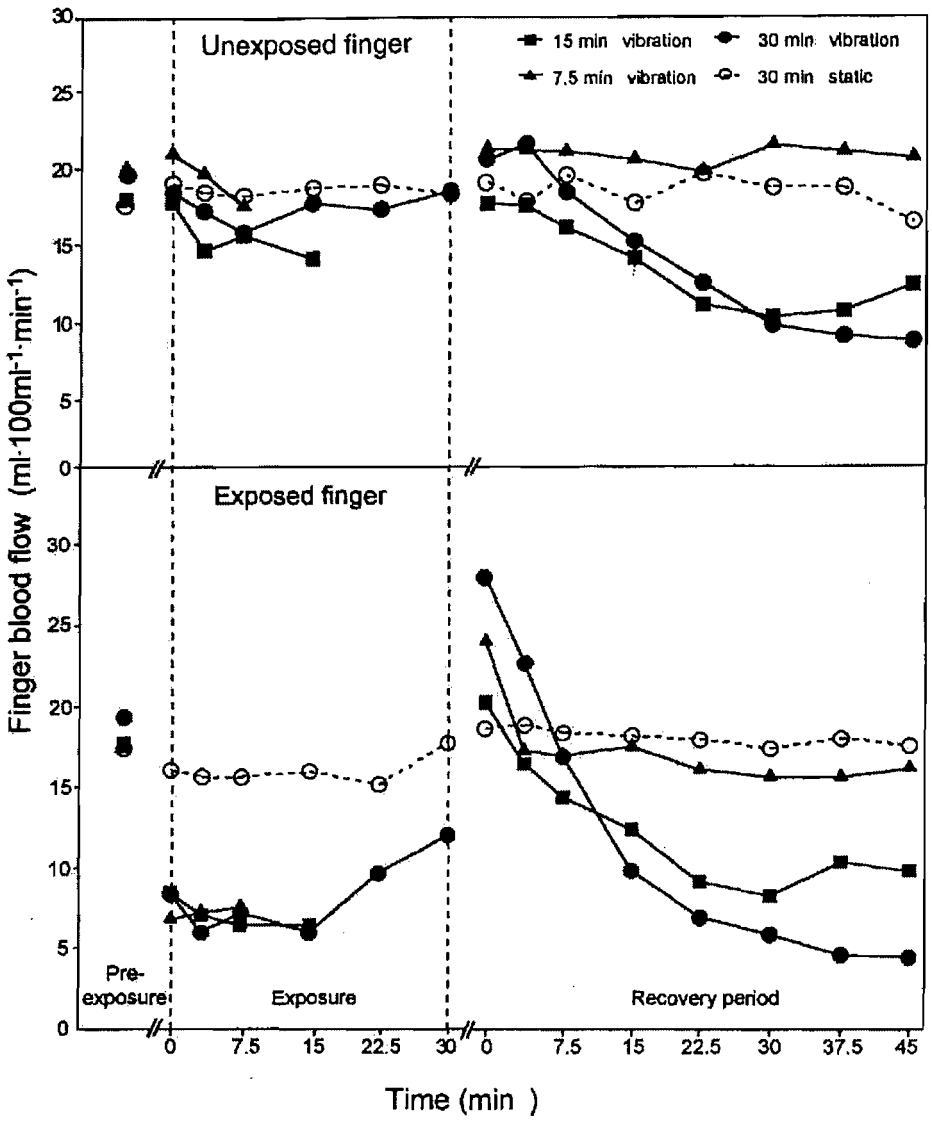


Figure 2-15 Mean values of finger blood flow of the exposed and unexposed fingers before, during and after exposure to static load and vibration of different durations (Bovenzi *et al.*, 1998).

Figure 2-16 shows the mean percentage changes in the finger blood flow of ten healthy men during and after exposure for 30 minutes to continuous vibration (top four graphs) and 30 minutes of intermittent vibration at 3.75 minute intervals (bottom four graphs) with a frequency of 125 Hz and an unweighted acceleration magnitude of 44 ms^{-2} r.m.s. (Bovenzi *et al.*, 2004). Between the intermittent periods of vibration exposure, Bovenzi *et al.* (2004) found that the finger blood flow in the exposed hand returned to the levels measured before vibration exposure (Figure 2-16). The return of finger blood flow in the exposed hand to pre-exposure levels when vibration ceases has been seen in other studies (Welsh, 1980; Egan *et al.* 1996; Bovenzi and Griffin, 1997; Bovenzi *et al.*, 1998, 1999, 2000).

No downward trend in finger blood flow was reported during the periods of rest over the test duration (Figure 2-16) with any duration of intermittent vibration (Bovenzi *et al.* 2004).

In contrast with previous studies (Welsh, 1980; Egan *et al.* 1996; Bovenzi and Griffin, 1997; Bovenzi *et al.*, 1998, 1999, 2000), Bovenzi *et al.* (2004) report that there were no statistically significant reductions in finger blood flow in the unexposed hand during continuous or intermittent vibration. The lack of vasoconstriction in the unexposed hand was attributed in part to the lower vibration magnitude used in the Bovenzi *et al.* (2004) study than in previous studies.

2.6.5.2 After vibration

Immediately after the cessation of vibration, Bovenzi *et al.* (1998) found an increase in finger blood flow in the exposed hand compared to blood flow measured before the exposure to vibration. Figure 2-15 shows the finger blood flow in the exposed and unexposed hand for 45 minutes after vibration exposure. The increase in finger blood flow in the exposed hand when vibration exposure ceases has been reported in other studies (Welsh, 1980, Egan *et al.* 1996). No increase in finger blood flow was reported in the unexposed hand by Bovenzi *et al.* (1998)

About 15 to 30 minutes after the end of vibration (with 15 and 30-minute exposure durations), Bovenzi *et al.* (1998) report significant vasoconstriction in both the exposed and the unexposed hand. The vasoconstriction in both hands was dependent on the duration of the vibration exposure: the 30-minute vibration exposure produced a greater reduction in finger blood flow than the 15 minute vibration exposure (Figure 2-15). Exposure for 7.5 minutes did not appear to produce vasoconstriction in the exposed hand after vibration.

As with previous studies (Welsh, 1980, Egan *et al.* 1996; Bovenzi *et al.*, 1998), Bovenzi *et al.* (2004) report an immediate vasodilation in the exposed hand following vibration exposure. The vasodilation occurred in the exposed hand regardless of whether the exposure was intermittent or continuous (Bovenzi *et al.* 2004). Figure 2-16 shows the percentage changes in the finger blood flow of ten healthy men during and after exposure to 30 minutes of continuous vibration and 30 minutes of intermittent vibration at 3.75-minute intervals (bottom four graphs) with a frequency of 125 Hz and an unweighted acceleration magnitude of 44 ms^{-2} r.m.s. (Bovenzi *et al.*, 2004). Figure 2-16 shows the vasodilation following vibration exposure.

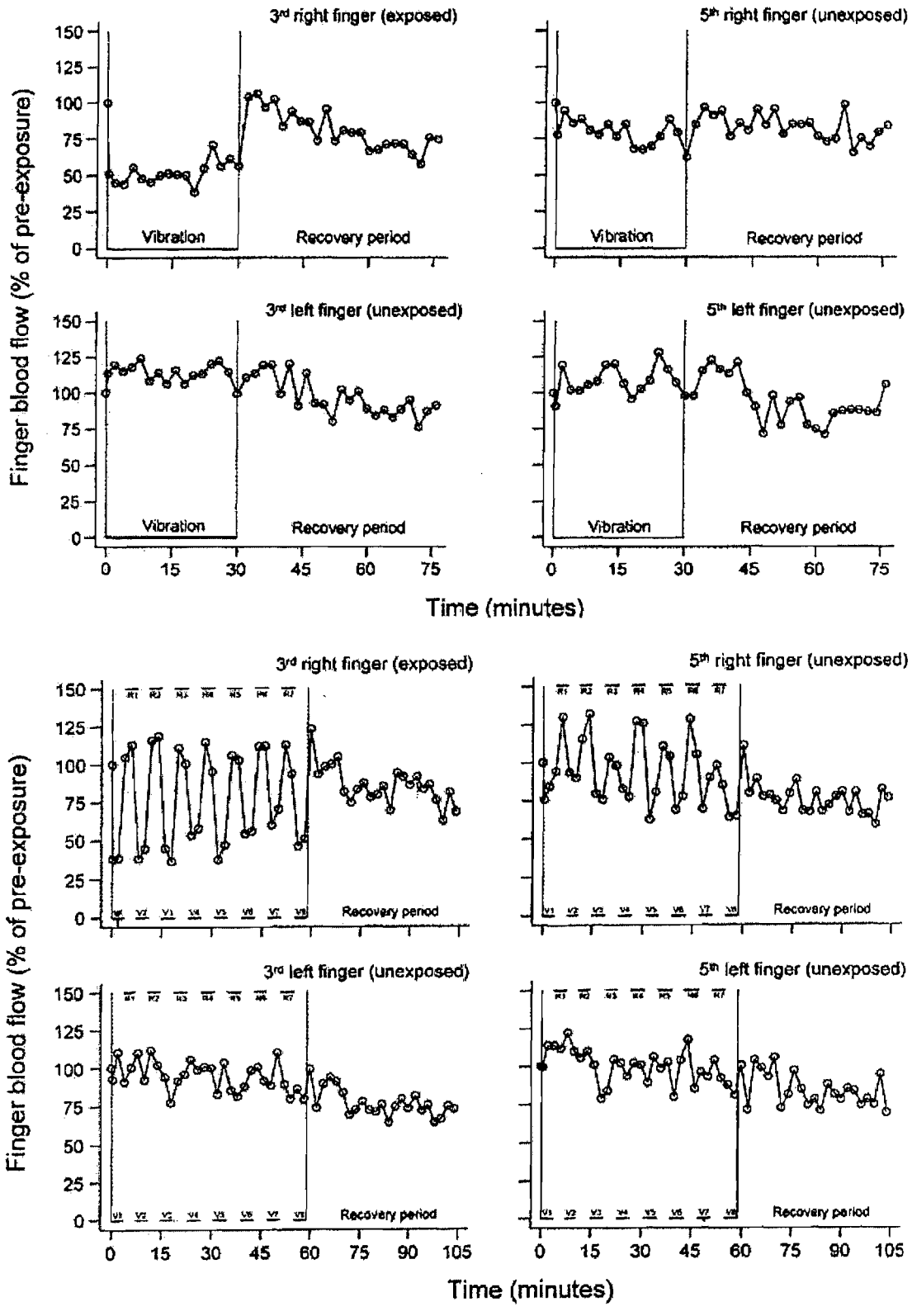


Figure 2-16 Mean percentage changes in the finger blood flow of ten healthy men during and after exposure to 30 minutes of continuous vibration (top four graphs) and 30 minutes of intermittent vibration at 3.75 minute intervals (bottom four graphs) with a frequency of 125 Hz and an unweighted acceleration magnitude of 44 ms^{-2} r.m.s. (Bovenzi *et al.*, 2004).

Following intermittent and continuous vibration exposure, Bovenzi *et al.* (2004) report a stronger vasoconstriction in the exposed hand following a continuous 30-minute exposure period than following intermittent vibration exposure. Bovenzi *et al.* (2004) suggest that there may be less risk to the vascular system with intermittent exposure than with continuous exposure, with the same total duration of exposure.

In previous studies, the vasoconstriction following vibration has been the same in the exposed and unexposed hands. Bovenzi *et al.* (2004) did not find a vasoconstriction in the unexposed finger following intermittent vibration exposure and suggest that the effects of intermittent vibration may be less severe than those of continuous vibration.

The greater vasoconstriction after longer durations of vibration than after shorter durations of vibration exposure as reported by Bovenzi *et al.* (2004) is consistent with the findings of Bovenzi *et al.*, 1998).

2.6.5.3 Conclusion

The vasoconstriction during vibration is not affected by the duration of the vibration exposure. The vascular response in the exposed hand and unexposed hand after vibration is, in part, determined by the vibration duration. The use of intermittent or continuous vibration exposure may change the dependence of finger blood flow after vibration on the vibration exposure duration.

2.6.6 Stimulus direction

No known studies have investigated the effect of vibration direction on finger blood flow.

2.6.7 Combinations of vibration characteristics

The dependence of finger blood flow on the separate independent vibration characteristics of frequency, magnitude, duration and direction has been described in Sections 2.6.3 to Section 2.6.6. There may be interactions between the effects of these variables.

2.6.7.1 During vibration

Few experimental studies have examined a possible interaction between independent vibration variables. Bovenzi *et al.* (2001) examined the effect on finger blood flow of an interaction between vibration magnitude and exposure duration by testing the $A(8)$ formula which is a measure of vibration dose expressed in International Standard ISO 5349 (2001). Section 2.9 summarises the ISO 5349 (2001) standard and the concepts of 8-hour energy-equivalent frequency-weighted

r.m.s. acceleration, $A(8)$, and the frequency-weighting.

Different combinations of vibration magnitude and exposure duration were compared by Bovenzi *et al.* (2001). Combinations were selected so that each exposure had an $A(8)$ of 1.4 ms^{-2} r.m.s. Figure 2-17 shows the mean values of finger blood flow measured in 10 healthy men before, during, and after exposures to vibration with different combinations of acceleration magnitude and duration but with the same 8-hour frequency-weighted acceleration magnitude of 1.4 ms^{-2} r.m.s. A similar degree of vasoconstriction occurred in the exposed hand during vibration at each combination of magnitude and exposure duration. The independence of vasoconstriction from vibration magnitude is in contrast to previous studies that have found a dependency of finger blood flow on vibration magnitude (Welsh, 1980; Egan *et al.*, 1996; Bovenzi *et al.*, 1999; Luo *et al.*, 2000).

The reduction in finger blood flow during vibration was stronger in the exposed hand than in the unexposed hand (Bovenzi *et al.*, 2001). Reductions in finger blood flow in the unexposed hand occurred at the highest magnitudes, 125 ms^{-2} r.m.s. during 3.75 minute's vibration exposure and 176 ms^{-2} r.m.s. during 1.88 minute's exposure. No reduction in finger blood flow in the unexposed hand occurred during exposure to lower vibration magnitudes and long exposure durations. Any interaction between vibration magnitude and duration seemed to affect the exposed and unexposed hand differently.

2.6.7.2 After vibration

Immediately after the end of vibration exposure, finger blood flow increased in the exposed hand (Bovenzi *et al.*, 2001) and is consistent with Welsh (1980), Egan *et al.* (1996), Bovenzi *et al.* (1998, 1999, 2001, 2004). The vasodilation in the exposed hand after vibration was independent of the magnitude and duration of the vibration exposure (Bovenzi *et al.*, 2001).

In the unexposed hand, the vascular response immediately after vibration exposure was less predictable than the response in the exposed hand. An increase in finger blood flow only occurred immediately following vibration exposure in two of the five conditions (30 minutes with 44 ms^{-2} r.m.s. and 7.5 minutes with 88 ms^{-2} r.m.s. at 125 Hz) The uncertain vascular response in the unexposed hand after vibration exposure is similar to that reported by Bovenzi *et al.* (2004) after intermittent vibration exposure and may be related to the combination of magnitudes and durations of exposure used by Bovenzi *et al.* (2001).

Following vasodilation, the longer durations of exposure with lower vibration magnitudes (30 minutes with 44 ms^{-2} r.m.s. and 15 minutes with 62 ms^{-2} r.m.s.) produced a reduction in finger blood flow in the exposed and unexposed hand. The reduction in finger blood flow was similar in the exposed hand and in the unexposed hand (Bovenzi *et al.*, 2001). Combinations of vibration exposures with greater acceleration magnitudes but shorter durations did not produce a reduction in flow after vibration exposure (Bovenzi *et al.*, 2001). The findings by Bovenzi *et al.* (2001) are consistent with Bovenzi *et al.* (1998) who reported a dependency of finger blood flow after vibration on vibration magnitude and with Bovenzi *et al.* (1999) who reported a dependence on vibration exposure duration. Bovenzi *et al.* (2001) state that when there were proportionate changes in both duration and magnitude, the changes in duration had the greater effect at 125 Hz.

2.6.7.3 Conclusion

The vasoconstriction during vibration seems to be influenced by the vibration magnitude more than the duration, whereas the vasoconstriction after vibration seems to be influenced more by the vibration duration than the magnitude.

The dependence of finger blood flow on vibration is complex. Further investigation of the separate and combined effects of vibration characteristics is required to

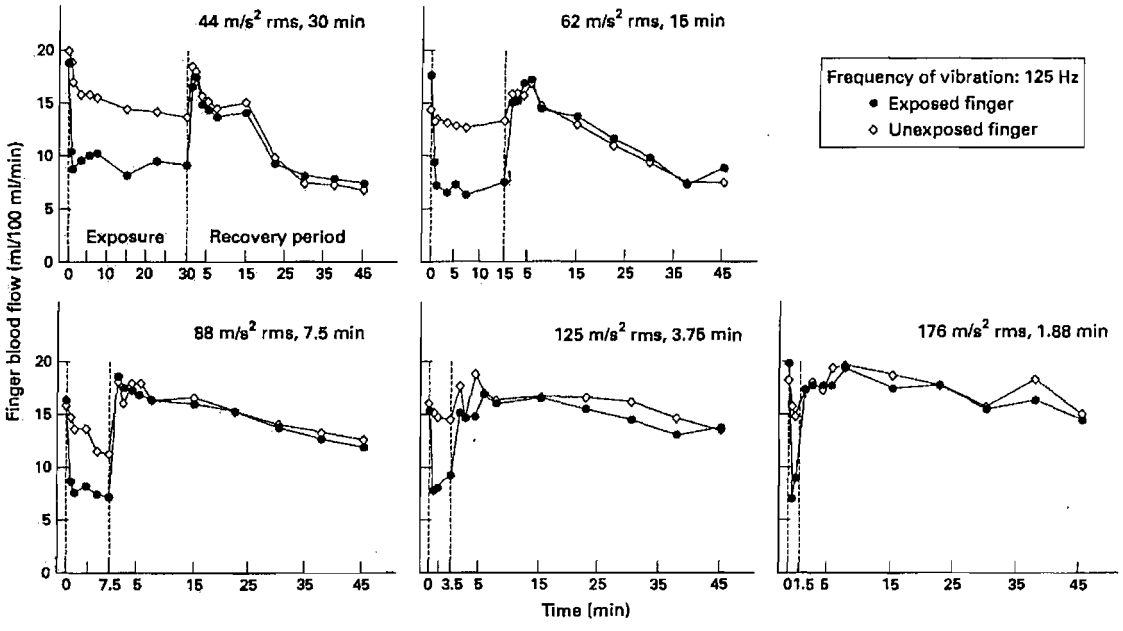


Figure 2-17 Mean values of finger blood flow measured in 10 healthy men before, during and after exposures to vibration with different combinations of acceleration magnitude and duration but with the same 8 hour frequency weighted acceleration magnitude of 1.4 ms^{-2} r.m.s. (Bovenzi *et al.*, 2001).

understand the dependence of finger blood flow on hand-transmitted vibration.

2.6.8 Stimulus force

The dependence of finger blood flow on force has been investigated in experiments that have controlled the magnitude of the applied force and the location of the applied force to the hand.

Bovenzi *et al.* (1995, 1998) found a push force of 10 N applied to the digits of the hand had no affect on finger blood flow compared with baseline measurements without force (Figure 2-15).

Bovenzi *et al.* (2006) found a 2-N push force applied to the finger reduced blood flow in the exposed digit for the 15-minute exposure duration, compared to blood flow before push force. Figure 2-17 shows mean finger blood flow and percentage finger blood flow before, during and after exposure to push force or push force and vibration (Bovenzi *et al.* 2006).

A 5-N push force applied to the middle phalanx of the exposed finger produced a

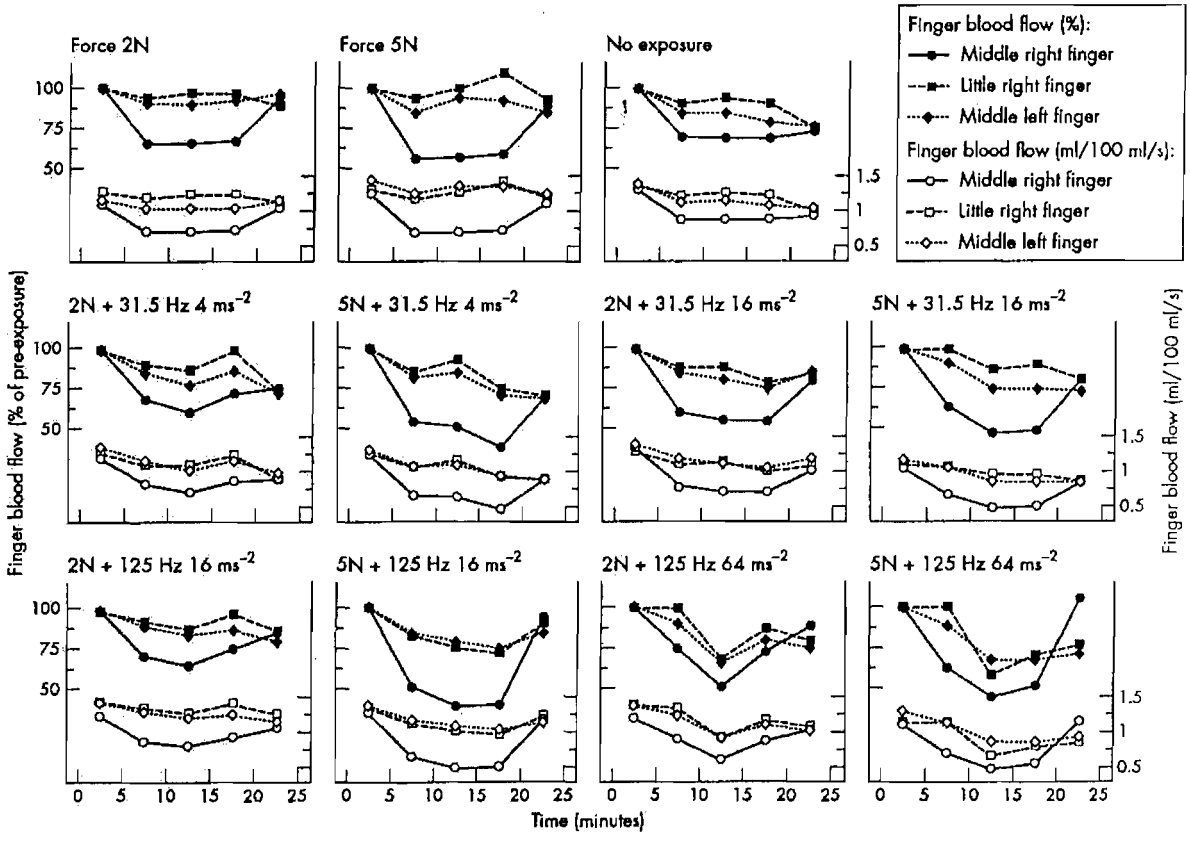


Figure 2-18 Mean and percentage change of finger blood flow in the exposed middle right finger and unexposed ipsilateral little right finger and unexposed contralateral middle left finger before, during and after exposure to push force and vibration (Bovenzi *et al.*, 2006).

stronger reduction in blood flow in the exposed digit than the 2 N push force. The unexposed contralateral hand showed no changed in blood flow during the application of force (Bovenzi *et al.*, 2006).

Bovenzi *et al.* (2006) identified that vibration with a 5 N push force caused a greater reduction in finger blood flow during vibration than vibration with a 2 N push force (Figure 2-18).

Griffin *et al.* (2006) applied both 5 N and 20 N forces to the palm. Figure 2-19 shows the effects of push force (5 or 20 N) and vibration [0 (no vibration or 125 Hz vibration] on the percentage change in finger blood flow during the exposure period of the experiment (Griffin *et al.*, 2006). The 20 N push force applied to the palm reduced finger blood flow compared to the 5 N force. Push force with vibration caused a stronger reduction in finger blood flow than push force alone.

2.6.8.1 Conclusion

A push force applied during exposure to vibration may confound the measurement of the dependence of finger blood flow on vibration.

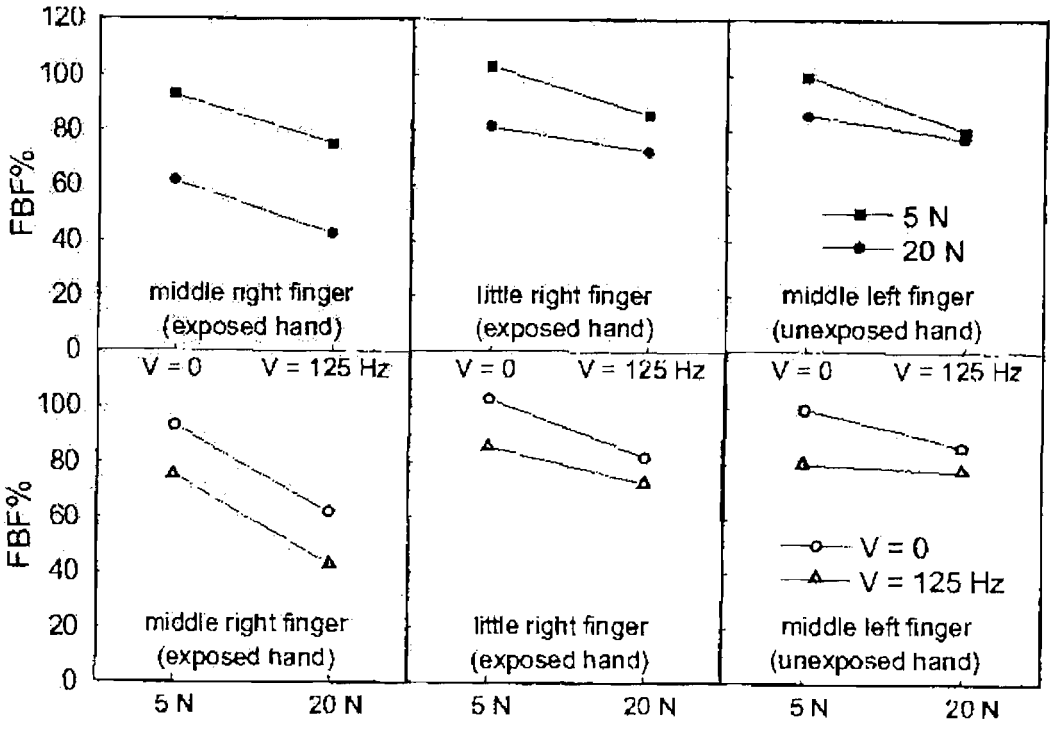


Figure 2-19 Effects of push force (5 or 20 N) and vibration [0 (no vibration0 or 125 Hz vibration] on the percentage change in finger blood flow during an exposure period (Griffin *et al.*, 2006).

2.7 THEORIES OF ACUTE VASCULAR RESPONSE TO VIBRATION

The pathophysiological mechanisms underlying the acute effects of vibration on finger blood flow have not been clarified in the literature. The vascular response to vibration could involve many mechanisms as the physiological mechanisms controlling and influencing finger blood flow are numerous. The main theory from the literature is outlined below.

2.7.1 During vibration exposure

Most studies have reported an immediate reduction in finger blood flow in the exposed and unexposed hand with the onset of vibration exposure (Bovenzi *et al*, 1998, 1999, 2001). Bovenzi *et al.* (2000) report that the immediate reaction of the digital blood vessels is consistent with a neurogenic reflex mechanism. The afferent and efferent pathways of a possible neural reflex mechanism are yet to be identified.

The reduction in blood flow in both the exposed and the unexposed hand during vibration is consistent with a central sympathetic vasomotor reflex mechanism (Egan *et al.,* 1996; Bovenzi *et al.,* 2000). External environmental stimuli activate neural afferent pathways to the brain. The sympathetic branches of the autonomic system provide the efferent signal to activate the sympathetic nerves in the blood vessels of the peripheral vasculature. Increased activation of the sympathetic nerves in the blood vessels cause vasoconstriction and a reduction in finger blood flow.

The dependence of finger blood flow on vibration frequency (Bovenzi and Griffin, 1997; Welsh, 1980; Furuta *et al.*, 1991) is consistent with the properties of the mechanoreceptors in the skin. The mechanoreceptors may be external environmental receptors that provide afferent sensory impulses to a centrally mediated mechanism.

The frequency of vibration could trigger the firing rate of a sensory impulse. Bovenzi *et al.* (2001) hypothesise that the vasoconstriction in the exposed and non-exposed hand during unilateral vibration may be due to vibration–induced increased activity of the peripheral mechanoreceptors in the fingers and hands producing an excessive efferent sympathetic outflow.

The significantly stronger reduction in the exposed finger than in the unexposed finger has been attributed to vasoconstrictor mechanisms of local origin (Griffin and Bovenzi, 1997; Bovenzi *et al.* 1999, 2001 and Kent *et al.*, 1991). Aaronson *et al.* (2004) state that local vasoconstrictor factors function primarily to regulate the blood flow in a local area.

2.7.2 After vibration exposure

Immediately after vibration exposure, a vasodilation in the exposed and non-exposed hand has been noted in some studies. This vasodilation may be consistent with a reduction of the sympathetic vasomotor tone due to a diminished discharge from the afferent skin mechanoreceptors or the sensory impulse no longer excited by the vibration stimulus (Bovenzi *et al.,* 2000). This hypothesis draws from studies by Griffin and Bovenzi (1997) and Bovenzi *et al.* (1999) who found a similar vascular response immediately after the cessation of unilateral vibration.

Bovenzi *et al.* (2001) state that the immediate vasodilation in the exposed hand but not in the unexposed hand following vibration exposure, may be due to a release of local vasodilatory substances possibly of endothelial origin. The lack of vasodilation in the unexposed hand in some studies (Bovenzi *et al.*, 1998; Bovenzi *et al.*, 2004) would support a locally mediated and locally acting response.

An alternative explanation provided by Bovenzi *et al.* (2001) is that vibration causes a vibration–induced impairment of the muscular vasoregulation function (either myogenic or neurogenic) of the terminal arteries.

In many studies a vasoconstriction in the exposed hand and in the unexposed hand has been seen 15 minutes after the end of vibration exposure. Bovenzi *et al.* (2000) hypothesise that this response may be due to a hyper-activity of the sympathetic nervous system induced by vibration.

Bovenzi *et al.* (2000) alternatively hypothesise that the delay in onset of the vasoconstriction during the recovery may be due to circulating vasopressor agents activated by vibration exposure. An equal reduction in finger blood flow in both hands and a long duration of the vasoconstriction during the recovery period suggests a long-lasting endocrine response.

2.8 MODEL

It is not yet possible to form a satisfactory 'model' of the mechanisms controlling vasoconstriction due to vibration because the data and understanding are insufficient to model the mechanisms. Figure 2-10 summarizes the previous findings that a model should fit and explain.

Figure 2-10 is an interpretation of current understanding of the current state of knowledge from the studies referred to in this chapter.

The diagram provides the structure around which the experiments in this thesis have been constructed.

Vibration applied to the right hand (exposed hand) activates a centrally mediated mechanism that reduces finger blood flow in the exposed hand and in the unexposed hand (i.e. the contralateral left hand). With locally mediated mechanisms active in the exposed hand, vasoconstriction in the exposed hand is stronger than the vasoconstriction in the unexposed hand. The reduction in blood flow remains constant for the duration of the exposure, assuming no change in the vibration frequency or the vibration magnitude.

The end of vibration exposure triggers a response from the centrally mediated

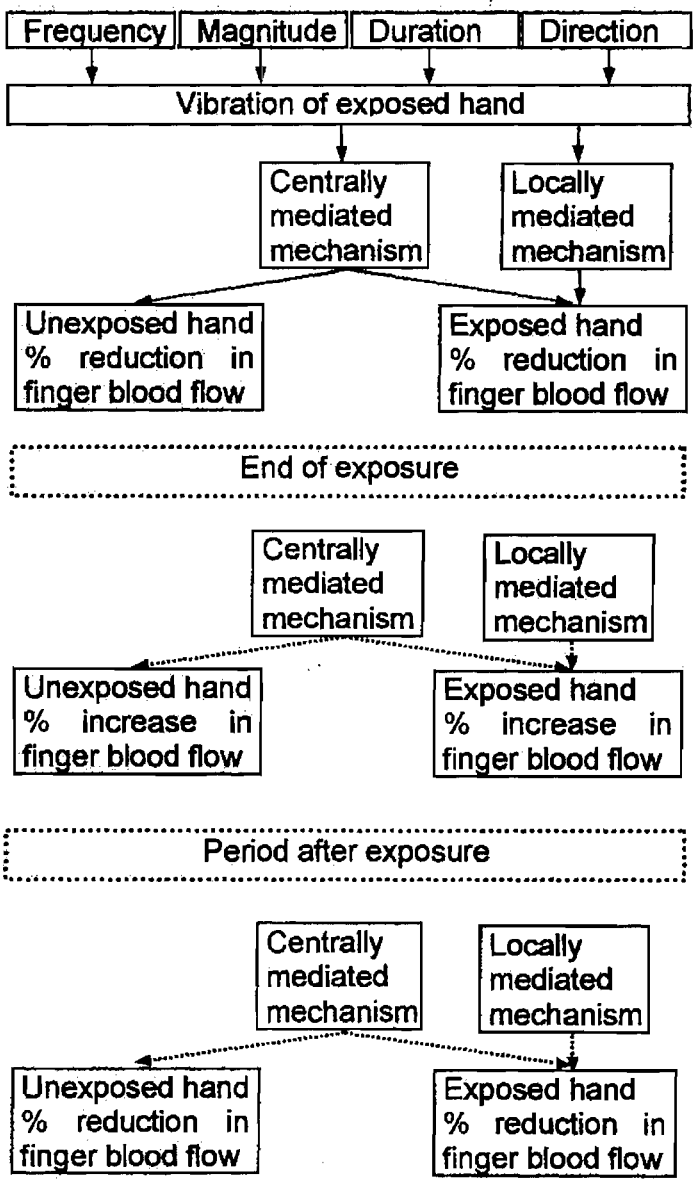


Figure 2-10 An interpretation of the variables affecting finger blood flow in exposed and unexposed hands during and after vibration exposure; based on studies reviewed in this chapter.

mechanism controlling the reduction of finger blood flow. An increase in finger blood flow occurs in the exposed hand and a weaker increase in finger blood flow occurs in the unexposed hand. With the end of vibration exposure, the locally mediated mechanism stops being active, causing vasodilation.

Fifteen to twenty minutes after the end of vibration, vasoconstriction occurs in the exposed and unexposed hands. The vasoconstriction may be stronger in the exposed hand than in the unexposed hand, depending on the vibration exposure characteristics and whether the locally mediated mechanism is restricting the blood flow in the exposed hand, in addition to the centrally mediated vasoconstriction that affects both hands.

After an unknown duration, finger blood flow in the exposed and unexposed hand returns to the level existing prior to vibration exposure.

2.9 INTERNATIONAL STANDARD 5349 (2001)

International Standard 5349 (2001) uses an 8-hour energy-equivalent frequency-weighted root-mean-square (r.m.s.) acceleration, $A(8)$, to define a dose-response relation for the prevalence of vibration-induced white finger.

The 8-hour energy-equivalent frequency-weighted root-mean-square (r.m.s.) acceleration, $A(8)$, is related to vibration magnitude and exposure duration:

$$A(8) = a_{rms}\sqrt{\frac{t}{T_{8h}}}$$

where a_{rms} is the frequency-weighted r.m.s. acceleration over the exposure duration, t, *and* T_{8h} is 8 hours. To keep the $A(8)$ value constant, a doubling of the vibration magnitude, a_{rms}, requires a fourfold reduction in exposure duration, t. Energy equivalence implies that an increase in the magnitude of vibration can be offset by a reduction in the duration of exposure (Bovenzi *et al.*, 2001).

The frequency weighting in ISO 5349 (2001) represents the assumed dependence on vibration frequency of the human response to vibration. The stronger the effect of frequency the stronger is the applied weighting. The current standard for hand-transmitted vibration assumes that the sensitivity of the hand-arm system to acceleration is inversely proportional to the vibration frequency at frequencies greater than 16 Hz. Below 16 Hz the current standard assumes that the sensitivity of the hand-arm system to vibration acceleration is independent of vibration frequency. The frequency-weighting curve in ISO 5349 (2001) has a slope of 0 dB at frequencies less than 16 Hz and -6 dB per octave at frequencies greater than 16 Hz. To calculate

the predicted risk to the human the vibration acceleration is therefore frequency-weighted.

Both the frequency weighting and the duration weighting in the standard are suspect. Some epidemiological studies have found that the frequency weighting defined in the standard gives poorer predictions of injury than unweighted vibration (e.g., Griffin *et al.*, 2003). The duration weighting used to formulate the $A(8)$ value allows short durations of very high acceleration to be considered safe (Griffin, 1995).

To predict the vascular response to vibration it is necessary to understand better the effects of vibration frequency, vibration magnitude and vibration duration on finger blood flow.

The experiments cited in Section 2.6 lead to the conclusion that during exposure to vibration the finger blood flow is dependent on the vibration magnitude and the vibration frequency. After the end of vibration exposure, finger blood flow is dependent on the frequency, duration and magnitude of the vibration exposure. One simple algorithm, such as $A(8)$, cannot predict two different responses during and after vibration exposure.

The apparent difference in finger blood flow between the exposed and unexposed hand makes prediction of blood flow during and after vibration further complicated.

The frequency weighting and $A(8)$ in ISO5349 (2001) cannot accurately represent the relationship between the vibration characteristics and finger blood flow in both hands. Understanding the relationships between the vibration characteristics and finger blood flow may assist the development of improved dose-response relationships for the hand-arm vibration syndrome.

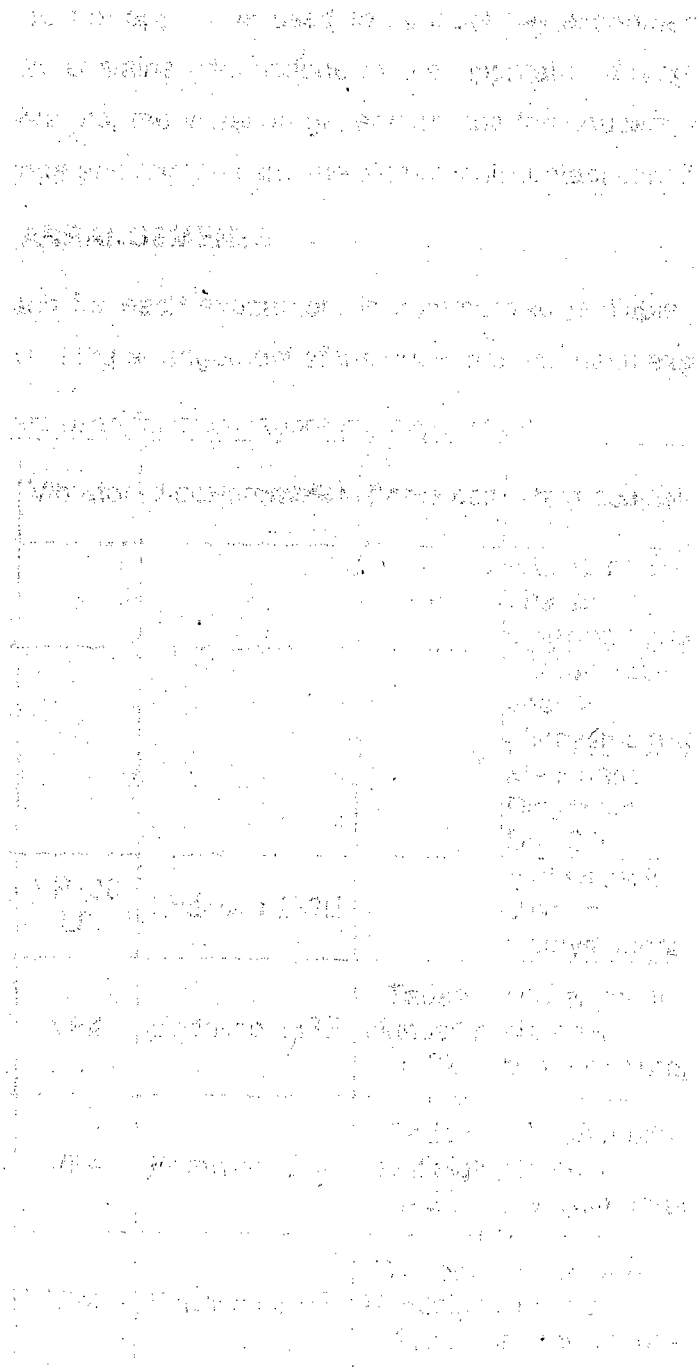
2.10 CONCLUSIONS

The overall aim of this thesis is to improve understanding of the effects of vibration on finger blood flow by investigating the dependence of blood flow on the frequency and magnitude of vibration.

The hypotheses underlying this research are:

- Previous observations of the effect of vibration on finger blood flow have been confounded by the effects of push force;
- Increasing the vibration magnitude reduces finger blood flow during vibration;
- Reductions in finger blood flow during exposure to vibration depend on the frequency of the vibration;

- Vibration produces similar reductions in blood flow in fingers on exposed and unexposed hands.



CHAPTER 3

APPARATUS

1.1 INTRODUCTION

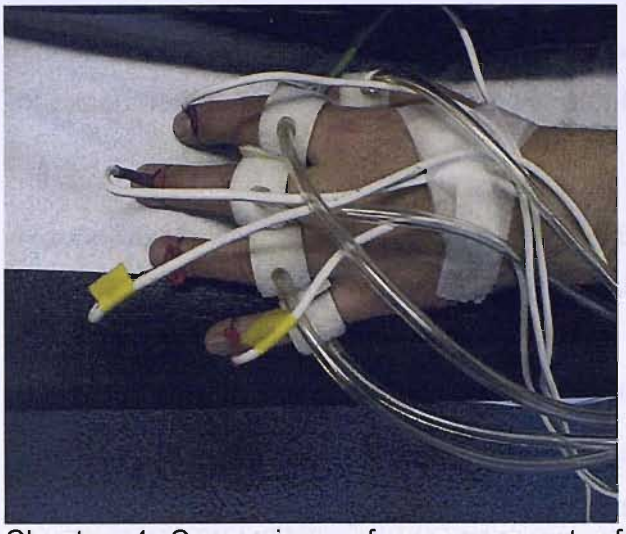
Chapter 3 describes the apparatus used to conduct the experimental work of the thesis. This chapter contains descriptions of the apparatus arrangement for each experiment, the vibrators, the vibration generation, the transducers, data acquisition systems, data storage and analysis and the skin-stimuli contact conditions.

1.2 APPARATUS ARRANGEMENTS

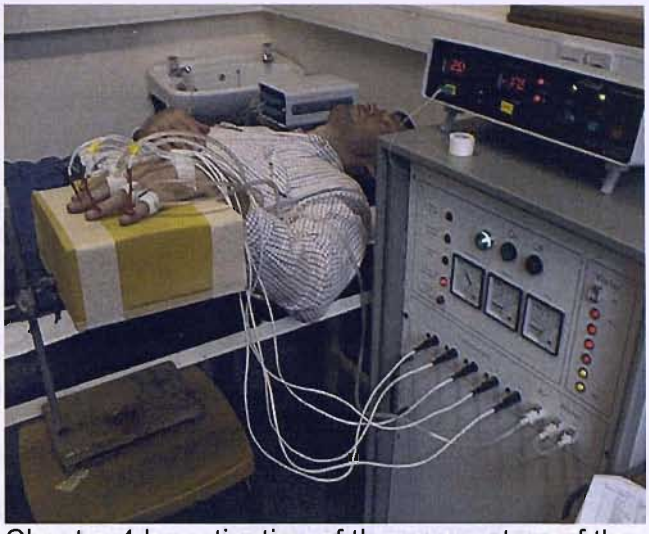
The equipment used for each experiment is summarised in Table 3-1. Figure 3-1 shows photographs of the arrangement of the equipment for each experiment

Table 3-1 Equipment used for each laboratory experiment

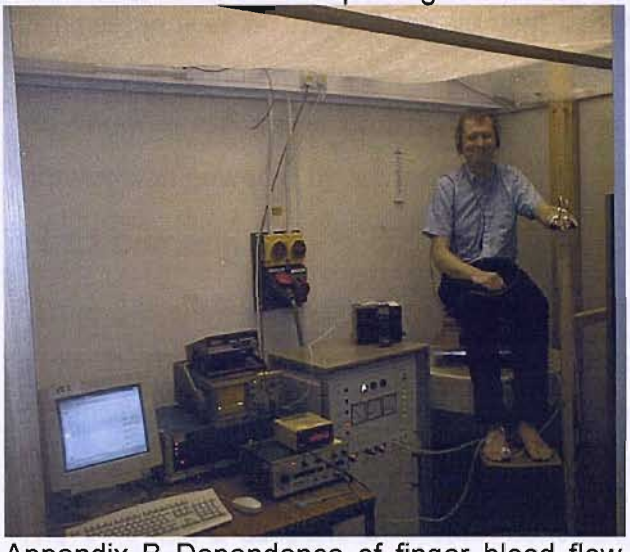
Experi-ment	Chapter	Vibrator	Accelerometer	Force cell	Data acquisition	Computer/data analysis software type
1	4	-	-	-	*HVLab* multi-channel plethysmograph	*HVLab* diagnostic software (v.4.23)
2	4				*HVLab* multi-channel plethysmograph	*HVLab* diagnostic software (v.4.23)
					Medimatic Digitmatic DM2000	Manual
3	Appendix B	VP180 LS	Endevco 233E		*HVLab* multi-channel plethysmograph	*HVLab* diagnostic software (v.4.23)
4	5	VP4	Endevco 233E	Tedea Huntleigh 1022	*HVLab* multi-channel plethysmograph	*HVLab* diagnostic software (v.5.108)
5	6	VP4	Endevco 233E	Tedea Huntleigh 1022	*HVLab* multi-channel plethysmograph	*HVLab* diagnostic software (v.5.108)
6	7	VP4	Endevco 233E	Tedea Huntleigh 1022	*HVLab* multi-channel plethysmograph	*HVLab* diagnostic software (v.6.001)
7	8	VP4	Endevco 233E	Tedea Huntleigh 1022	*HVLab* multi-channel plethysmograph	*HVLab* diagnostic software (v.6.1.017)
		VP30	Endevco 233E	DS LT-05A5		



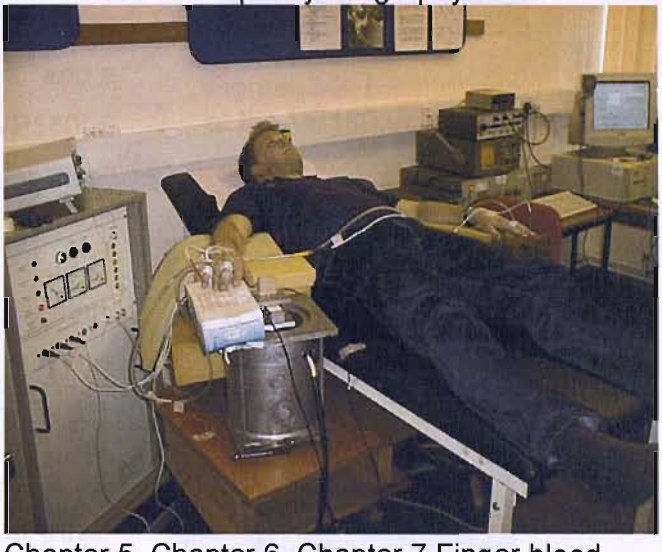
Chapter 4 Comparison of measurement of blood flow on one or multiple fingers.



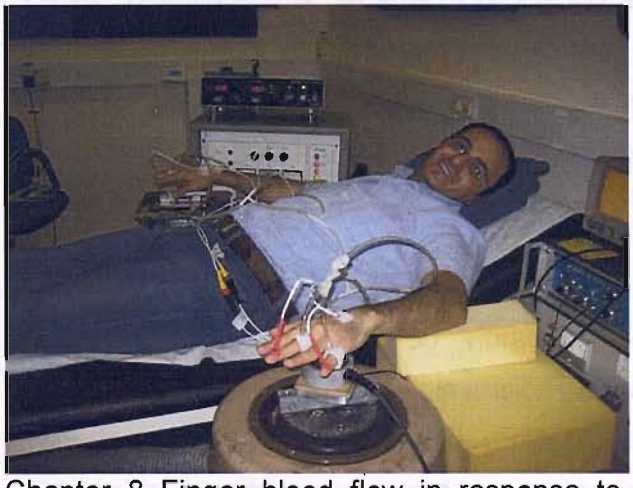
Chapter 4 Investigation of the parameters of the venous occlusion plethysmography method



Appendix B Dependence of finger blood flow on whole-body vibration



Chapter 5, Chapter 6, Chapter 7 Finger blood flow in response to vibration and push force to one hand



Chapter 8 Finger blood flow in response to vibration and push force to one or two hands

Figure 3-1 Photographs of the arrangement of the equipment used in the experiments in Chapters 4 to 8 and Appendix B

1.3 VIBRATORS

Three electro-dynamic vibrators were used to provide the vibration stimuli in the set of experiments. A description of each vibrator is given below.

1.3.1 Derritron VP180

Figure 3.2 shows the exterior view of the VP180LS, used in the experiment in Appendix B. The dimensions of the vibrator are: height 803 mm, width 794 mm and mass 1152 kg. A trunion was not used with the vibrator.

Figure 3-2 Exterior view of the VP180 vibrator

The VP180LS has a suspension system consisting of 6-link arms. The vibrator supports a static load of 79 kg. The vibrator is capable of producing a peak-to-peak displacement of 50 mm in the vertical direction in the vertical direction, a maximum velocity of 7.62 m s^{-1} and a maximum acceleration of 315 m s^{-2}. The VP180LS vibrator was powered by a Derritron 1500 watt amplifier.

1.3.2 Derritron VP4

Figure 3-3 shows the exterior view of the VP4 vibrator, used in the experiments in Chapters 5 to 8. The dimensions of the vibrator are: height 260 mm, width 337 mm, mass 45.5 kg. A trunion was not used.

Figure 3-3 Exterior view of the VP4 vibrator with a metal plate and force cell on the top

The VP4 has a suspension system consisting of three flexible spiders. The vibrator supports a static load of 1.8 kg. The vibrator is capable of producing a peak-to-peak displacement of 6.35 mm in the vertical direction, a maximum velocity of 1.27 ms^{-1} and a maximum acceleration of 309 ms^{-2}. The VP4 vibrator was powered by a 100 watt amplifier (Derritron TA120).

1.3.3 Derritron VP30

Figure 3-4 shows the VP30 vibrator used in the experiment in Chapter 8. The dimensions of the vibrator (with trunion) are: height 508 mm, width 546 mm, mass 291 kg. The vibrator was mounted in a rigid trunion.

Figure 3-4 Exterior view of the VP30 vibrator

The VP30 has a three-link arm suspension system that supports a static load of 22.7 kg. The vibrator is capable

of producing a peak-to-peak displacement of 11.5 mm in the vertical direction, a maximum velocity of 0.7 m s^{-1} and a maximum acceleration of 392 ms^{-2}.

The VP30 vibrator was powered by a 300 watt amplifier (Gearing and Watson SS_600).

1.4 VIBRATION GENERATION

In the experiment in Appendix B a sinusoidal waveform was generated using the VP180LS function generator. The acceleration waveform was monitored using an oscilloscope.

In the experiments in Chapters 6 and 7 a sinusoidal waveform was generated using a function generator and passed to the VP4 vibrator via a power amplifier. The magnitude of the waveform was controlled by a computer system (*HVLab* version 3.81) via a multiplying digital-to-analogue converter. .

In the experiment in Chapter 8 sinusoidal waveforms were generated by two function generators, one connected to the VP4 and the other connected to the VP30. The acceleration signals from accelerometers were monitored using an oscilloscope.

1.5 TRANSDUCERS

A transducer is a device for converting an electrical signal from another form of energy e.g. from acceleration to voltage.

1.5.1 Accelerometers

Accelerometers were used to monitor the vibration acceleration magnitude output from the vibrators to ensure the subjects were exposed to the correct vibration.

1.5.1.1 Endevco 322 E

A piezo-electric Endevco 322 E accelerometer was used in all experiments with vibration (Figure 3-5). To monitor the magnitude of the vibration waveform in the experiment in Appendix B an accelerometer was attached to the underside of the wooden seat.

In the experiments in Chapters 5 to 8 an accelerometer was attached to the underside of a metal plate. Two Endevco 322E accelerometers were used in study seven, one under each metal plate.

Figure 3-5 Endevco 322E accelerometer

The signals from the accelerometers were passed through charge amplifiers (Fylde).

1.5.2 Force cells

In the experiments in Chapters 5 to 8, force cells were used to monitor the push force applied by the hand of the subject to a wooden platform. The outputs from the force cells were shown on a force meter via an amplifier. The force cells enabled the subjects to monitor and control the push force applied by their hand.

1.5.2.1 Tedea Huntleigh 1022

Figure 3-6 shows the exterior of a Tedea Huntleigh force cell attached between a vibrator and a metal plate.

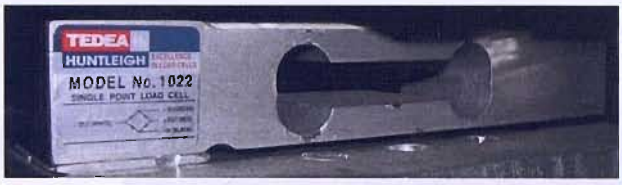


Figure 3-6 Exterior view of a Huntleigh force cell

The Huntleigh 1022 is a single point aluminium load cell. The dimensions of the load cell are: 80 mm length and 12.6 mm depth and width.

1.5.2.2 DS LT-05A5

A piezo-resistive DS LT-05A5 force cell (Figure 3-7) was used in the experiment in Chapter 8 to measure the push force applied by the left hand.

The dimensions of the force cell are: 50 mm diameter, 25 mm height.

This force cell had a 10 kg range.

Figure 3-7 Exterior view of a DS LT-05A5 load cell

1.5.3 Force meter

A force meter was used to indicate the push force applied by the hand of the subject, in the experiments in Chapters 5 to 8. Figure 3-8 shows a force meter.

The force meter was connected to the force cell and calibrated to set an applied 2-N push force to position the needle at ION. The force cell was calibrated before each experimental session. The force cell was calibrated by applying a 2-N weight to the top of the metal platform.

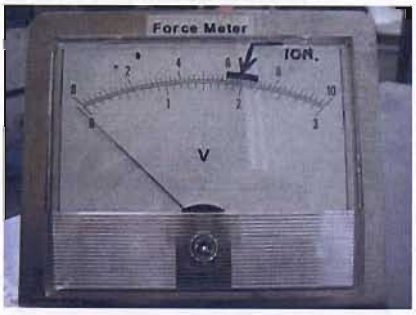


Figure 3-8 Front view of force meter

In the experiment in Chapter 8, two force meters were used to indicate the push force applied by each hand.

1.5.4 Strain gauges

Mercury-in-silastic strain gauges were used to monitor the change in volume of the finger in all experiments. *HVLab* strain gauges were used for all experiments. In the second experiment in Chapter 4, Medimatic strain gauges were also used.

A strain gauge consists of a complete circuit loop of mercury held within a thick silicone tube. The mercury is a conductor and measures the voltage across the terminals of the mercury loop, with constant current excitation. As the strain gauge increases in size due to a volume change, the resistance around the mercury loop changes. The change in resistance is measured as a voltage drop.

1.5.4.1 *HVLab* strain gauges

Figure 3-9 shows a red *HVLab* strain gauge with a circumference of 41 mm. *HVLab* strain gauges are available in four sizes according to the circumference of the silicone tube. A green gauge has a circumference of 49 mm, a yellow gauge a circumference of 57 mm and blue gauges have a circumference of 65 mm. *HVLab* strain gauges are designed to be used with the *HVLab* multi-channel plethysmograph.

Figure 3-9 External view of a red *HVLab* strain gauge

The *HVLab* strain gauges use a four terminal lead arrangement (Figure 3-10).

The four terminal lead arrangement measures the resistance across the mercury loop inside the silicone tube, as indicated by the bold circles in Figure 3-10.

1.5.4.2 Medimatic strain gauges

Figure 3-11 shows a red Medimatic strain gauge. Medimatic strain gauges are available in different sizes according to the circumference of the silicone tube.

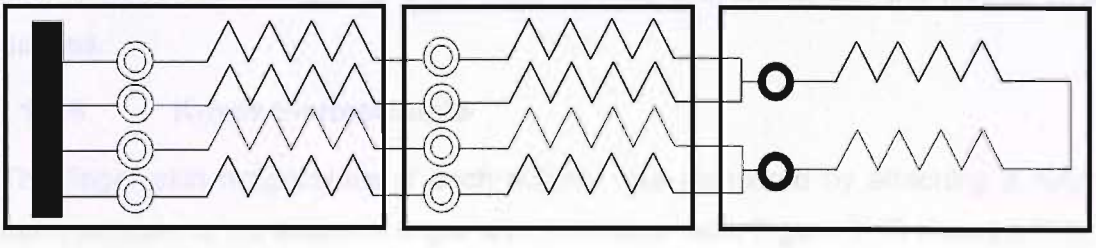


Figure 3-10 *HVLab* four-terminal lead arrangement showing sections of electronic resistance. Bold circles indicate the points at which resistance is measured.

Medimatic strain gauges are designed to be used with the Medimatic Digitmatic DM2000 plethysmograph.

The Medimatic plethysmograph uses a two terminal lead arrangement (Figure 3-12). The two terminal lead arrangement measures the resistance across the mercury loop within the plethysmograph, at the point indicated by the bold circles in Figure 3-12.

Figure 3-11 A red Medimatic strain gauge

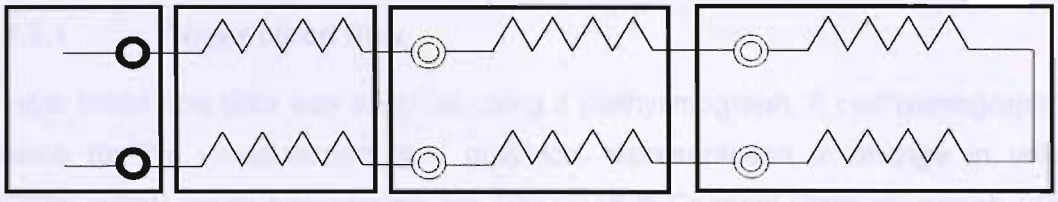


Figure 3-12 Medimatic two-terminal lead arrangement showing sections of electronic resistance. Bold circles indicate the points at which resistance is measured.

1.5.5 Strain gauge adaptor and strain gauge extension cables

A strain gauge adaptor was devised to enable the use of *HVLab* strain gauges with the Medimatic Digitmatic DM2000 plethysmograph in the second experiment in Chapter 4.

In the experiments in Chapters 5 to 8 *HVLab* strain gauges were plugged into strain gauge extension cables to extend the length of the gauges. This was for measurement on fingers at a distance from the plethysmograph.

The function of the strain gauges was not affected by the strain gauge adaptor or the extension cables because of the 4-terminal lead arrangement in the *HVLab* strain gauges.

1.5.6 K-type thermocouple

The finger skin temperature of each subject was measured by attaching a K-type thermocouple to the subject's finger with micropore tape. Figure 3-13 shows a K-type thermocouple. The thermocouple was attached to an *HVLab* thermal aesthesiometer which displayed digitally the skin temperature, within 0.1 °C.

Room temperature was measured by attaching a K-type thermocouple to the wall near the head of the subject with micropore tape. The room temperature was also displayed digitally on the *HVLab* thermal aesthesiometer.

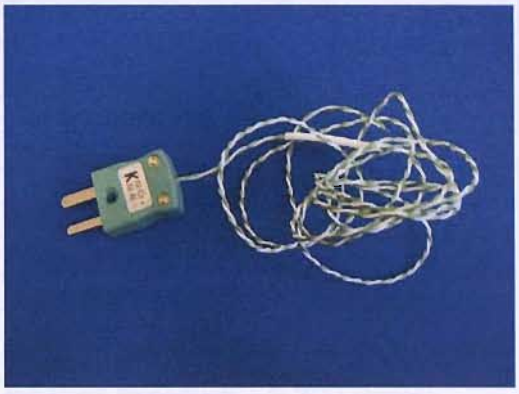


Figure 3-13 K-type thermocouple

1.6 DATA ACQUISITION

1.6.1 Finger blood flow

Finger blood flow data was acquired using a plethysmograph. A plethysmograph is a device for the measurement and graphical representation of change in volume (Griffin, 1990). In all experiments the *HVLab* Multi-Channel Plethysmograph (ISVR, University of Southampton) was used. In the second experiment in Chapter 4, a Digitmatic DM2000 (Medimatic A/S, Copenhagen) was also used.

1.6.1.1 *HVLab* multi-channel plethysmograph

The *HVLab* multi-channel plethysmograph (ISVR, University of Southampton) consists of a power supply unit, a plethysmograph, strain gauge transducer and cuffs linked by tubing to each other and the plethysmograph.

Figure 3-13 shows the exterior view of a plethysmograph. Table 3-2 gives the dimensions of an *HVLab* multi-channel plethysmograph.

The *HVLab* system allows simultaneous measurements of blood flow at five locations; it is computer-controlled and stores individual blood flow curves as well as individual and mean slopes within the computer software.

Figure 3-14 Exterior view of an *HVLab* Multi-Channel Plethysmograph

Table 3-2 The specification details of the *HVLab* multi-channel plethysmograph system	
Hardware dimensions:	
Height	1034 mm
Length	492 mm
Width	552 mm
Mass	85 kg
Software selected parameters:	
Number of test fingers	1-5
Inflation Pressure	0-300 mmHg
Fixed parameters	*HVLab*
Cuff inflation rate	>300 mmHg s-1
Strain gauge resistance range	0.25 – 0.8 ohm
Data sampling rate	18 samples s-1

The *HVLab* system measures and compensates for the strain gauge cable resistance around the finger. The cuff inflation pressure compensates for the volume of air contained in the tubes between the cuff and the plethysmograph.

1.6.1.2 Digitmatic DM2000

Figure 3-15 shows the exterior view of a Medimatic Digitmatic DM2000. The Digitmatic DM2000 (Medimatic A/S, Copenhagen) consists of an internal power supply, a plethysmograph, strain gauge transducers and cuffs linked by tubing to the plethysmograph.

Table 3-3 shows the specification details of the Digitmatic DM2000 plethysmograph system.

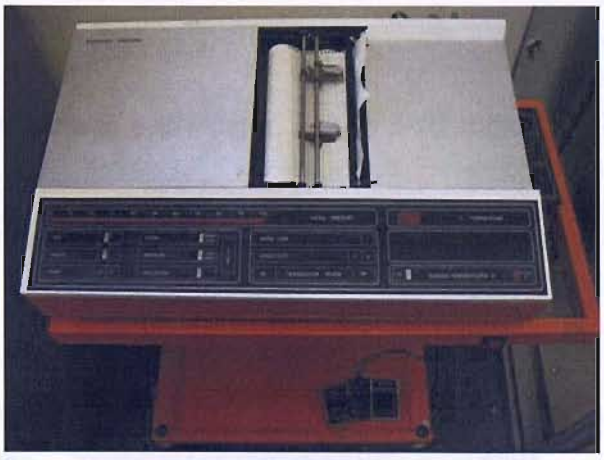


Figure 3-15 Exterior view of a Medimatic Digitmatic DM2000

The Medimatic allows simultaneous measurements at two locations. It does not easily allow accurate control of air pressure since it does not compensate for the volume of air in the tubing and cuffs.

Table 3-3 Specifications of the Medimatic Digitmatic DM2000 plethysmograph system	
Hardware dimensions:	
Height:	960 mm
Width:	720 mm
Depth:	48 mm
Mass:	60 Kg
Software selected parameters:	
Number of test fingers	1-2
Inflation Pressure	0-300mmHg
Fixed parameters	Medimatic
Cuff inflation rate	Unknown
Strain gauge resistance range	N/A
Data sampling rate	Analogue

1.6.2 Calibration of a plethysmograph

1.6.2.1 Maintenance calibration

The strains measured by the two plethysmographs were investigated by connecting two dummy electrical resistors: a resistance of 0.5 ohms in parallel with a 50 ohm resistor, and a resistor of 10 ohms in parallel with a 100 ohm resistor. The occlusion pressures were calibrated by measuring the pressure at the cuff with a manometer in comparison with the pressure supplied by the plethysmograph.

1.6.2.2 Automatic pre-measurement calibration

At the start of each finger blood flow measurement, the resistance of the strain gauge around the finger was measured. The change in finger volume during venous occlusion was therefore relative to the resistance of the strain gauge around the finger at the start of the measurement.

1.6.3 Pressure Cuffs

Single-inlet air cuffs were used to apply pressure to each finger. Figure 3-16 shows a single-inlet air cuff.

Manufactured cuffs were constructed of a thin plastic bag, rectangular in shape.

For the measurement of finger blood flow using venous occlusion plethysmography pressure cuffs were wrapped around the fingers. The cuffs were kept in position by Velcro tabs that were tightened to fit the finger more accurately. The Velcro also constrained the air bags so expansion was inwards tightening around the finger rather

Figure 3-16 Single-inlet air cuff used to occlude venous flow in the digits

than expanding outwards.

Cuffs were manufactured to be air tight so no pressure is lost during occlusion.

When multiple cuffs were used these were joined by equal lengths of tubing, so pressure was equalized and applied simultaneously in each cuff. The cuffs were attached by tubing to the single air outlet on the plethysmograph.

I.7 DATA STORAGE AND PROCESSING

1.7.1 Vibration and push force

The vibration characteristics and push force were monitored during the experimental session but no data were recorded as these data were not required for analysis.

1.7.2 Finger blood flow

Two methods were used to store and process finger blood flow data dependent on the plethysmograph being used.

1.7.2.1 *HVLab* Diagnostic Software

The *HVLab* multi-channel plethysmograph is computer-controlled by the *HVLab* finger blood flow programme, part of the *HVLab* Diagnostic Instruments Manager software. The software was designed to measure finger blood flow. The *HVLab* plethysmograph produces a computer-generated graphical representation of the increase in finger volume over time.

Figure 3-17 shows an example of a graphical representation of the increase in finger volume over time recorded on five fingers following occlusion by the *HVLab* multi-channel plethysmograph.

The slope of the blood flow curve was estimated automatically by the computer from the increase in strain. The experimenter was able to review and adjust the slope if necessary. The computer recorded the increase in blood flow as determined by the blood flow slope and stored the data in the *HVLab* diagnostic instruments manager software.

Figure 3-17 Change in strain recorded on 5 fingers following occlusion by the *HVLab* multi-channel plethysmograph

1.7.2.2 Medimatic

The Medimatic plethysmograph provided a paper record of results over time at 2.5 mm per second. The slope of the blood flow curve was estimated by the experimenter from the increase in strain. Data was stored by collating data points and entering them into a spreadsheet.

Figure 3-18 shows an example of a graphical representation of the increase in finger volume over time recorded on five fingers following occlusion by the *HVLab* multi-channel plethysmograph

1.7.3 Finger skin temperature

In all experiments a finger skin temperature reading was displayed on the *HVLab* thermal aesthesiometer and was manually recorded each minute.

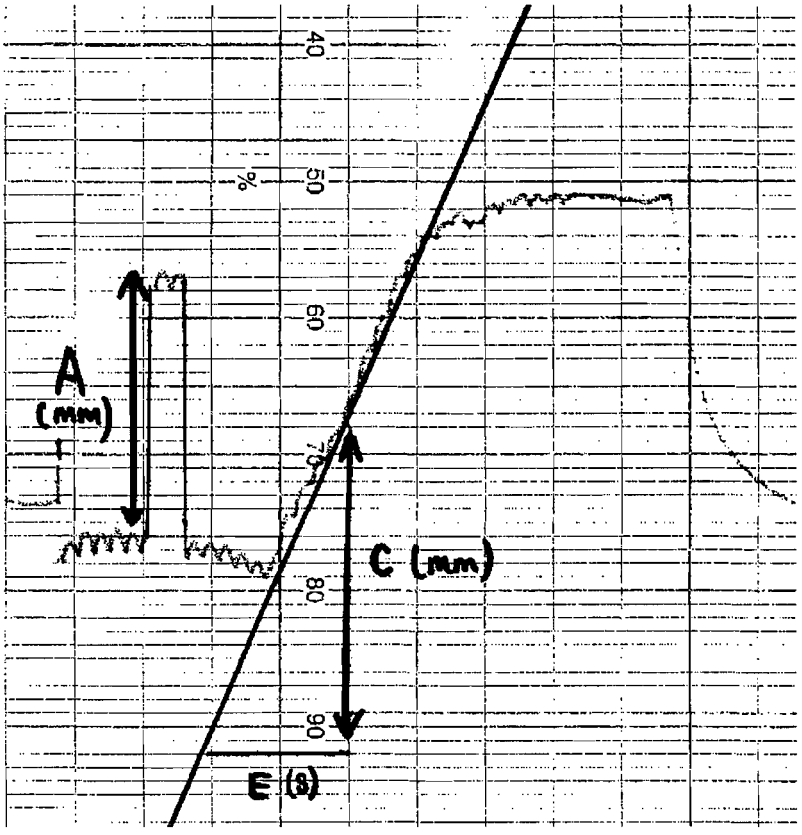


Figure 3-18 Change in strain recorded on one finger following occlusion by the Medimatic Digitmatic DM2000 plethysmograph

For single measurements the thermocouple was held between the thumb and forefinger or between the thumb and middle finger until the indicated skin temperature stabilised. For repeated measurements the thermocouple was taped to the dorsal surface of the finger using micropore tape.

1.7.4 Room temperature

In all experiments, a room temperature reading was displayed on the *HVLab* thermal aesthesiometer and was manually recorded each minute.

1.7.5 Medical questionnaire

A medical questionnaire was completed by each subject prior to commencing each experiment. A copy of the medical questionnaire is in Appendix A.

Subjects were supplied with a guidance letter to avoid coffee, tea, coke, alcohol, smoking or vibrating tools for 2 hours. A copy of the guidance is in Appendix A.

1.7.6 Anthropometric data

Finger dimensions were measured using Vernier callipers to an accuracy of 1.0 mm. Measurements of finger breadth, width and length were made at the interphalangeal

joints. Finger and phalanx lengths were measured using the criteria given by Garrett (1970).

Finger volumes and surface areas were calculated assuming the finger took the form of an elliptical cylinder.

1.8 SKIN-STIMULI CONTACT LOCATIONS

Different skin-stimuli contact sources were achieved by changing the size, shape and location of the wooden block attached to the shaker.

In the experiment in Appendix B the buttocks were the main contact between person and shaker. Figure 3-19 shows a wooden rigid seat used to contact the buttocks with the shaker in experiment three

Figure 3-19 Wooden rigid seat used to contact buttocks with shaker in Experiment 3

In the experiment in Chapter 5 a wooden platform was secured on top of a metal plate so that the middle phalanx of a subject's right middle finger could be placed on the wooden plate with the remaining fingers suspended in air (Figure 3-20). The height and width of the wooden platform was 40 mm and the depth was 12 mm.

Figure 3-21 shows a domed wooden platform for palm or finger contact in the experiments in Chapters 6 to 8. The diameter of the circular contact was 25 mm, the radius of curvature of the dome being 25 mm.

In the experiment in Chapter 6, the domed cylinder of wood was secured on top of a metal plate so the middle of a subject's right palm or the medial phalanx of the right middle finger could be placed on the wooden plate with all fingers (except right middle finger in some conditions) suspended in air.

In the experiment in Chapter 7, the right palm of the subject was in contact with the domed platform with all fingers suspended in air. In the experiment in Chapter 8 two domed wooden platforms were used for contact with the left and right palms.

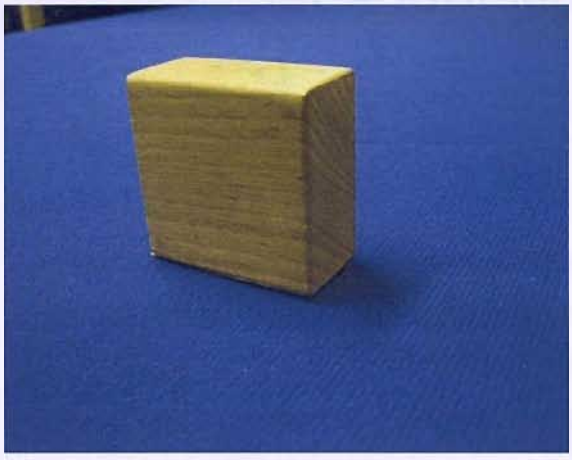


Figure 3-20 Cubed wooden platform for finger contact with shaker in the experiment in Chapter 5.

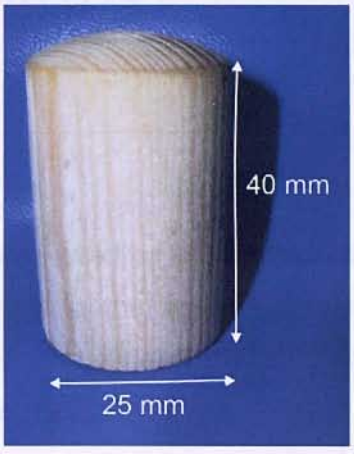


Figure 3-21 domed wooden platform for palm and finger contact in the experiments in Chapters 6 to 8.

CHAPTER 4

MEASUREMENT METHOD

4.1 INTRODUCTION

In this thesis arterial blood flow to the fingers was measured by the venous occlusion strain gauge plethysmographic technique, according to the method proposed by Greenfield *et al.* (1963). A plethysmograph is a device for the measurement and graphical representation of change in volume (Lewis, 1996).

A mercury-in-silastic strain gauge was placed around the distal phalanx and an air cuff was fitted around the proximal phalanx of each of the test fingers. The cuffs were positioned in this way to avoid measurement artefacts during inflation e.g. a jump in the trace (Greenfield *et al.*, 1963). The cuff was connected to the pneumatic system of a plethysmograph. Cuffs were fitted so there was no constriction of the finger when the cuff was deflated. The strain gauge was always in slight extension but not so tight as to restrict blood flow.

There are three components of a finger blood flow (FBF) measurement: (i) the calibration pulse, (ii) the application of venous occlusion by the air cuff, and (iii) the measurement of finger volume by the strain gauge.

During the calibration pulse, the resistance of the strain gauge was measured before occlusion was applied. This is the baseline strain gauge resistance.

On instruction, the plethysmograph inflated the air cuff to the desired air pressure applying venous occlusion to the finger. The air pressure was between 30 and 100 mmHg, and the occlusion duration was five or eight seconds, depending on the experiment. Venous occlusion stopped the blood leaving the finger beneath the cuff, but still allowed arterial inflow.

During venous occlusion, the plethysmograph indicated the increasing finger volume by measuring the corresponding increase in resistance of the strain gauge over a period of a few seconds. The change in resistance (assumed to be proportional to strain) was recorded as a relative percentage change from the baseline resistance measured during the calibration pulse (Lewis, 1986). The method assumes that the digit is cylindrical and that the volume changes in the transverse direction and not in

the longitudinal direction. The percentage change in strain was graphically recorded as a blood flow curve.

Changes in finger volume were determined by fitting a tangent to the blood flow curves following venous occlusion. Standardised positioning of the slope was needed to maintain consistency across measurements. The first 1-second of the blood flow curve after venous occlusion was ignored, as this can contain artefacts caused by the pressurisation of the cuff. The tangent was formed from a line joining either the systolic peaks or the diastolic troughs of the blood flow curve over the steepest period between 1 second and 2 seconds after the application of the occlusion pressure.

The gradient of the trace after venous occlusion was assumed to indicate the rate at which blood entered the finger. The blood inflow (A_{in}), was measured in ml of blood per 100ml of tissue per second (which is equivalent to the percentage increase in finger volume per second), calculated from the rate of increase in strain using:

$$A_{in} = \frac{C}{A.E}$$

where A (mm) is the height of a calibration pulse corresponding to a 1% increase in finger volume, and C (mm) is the increase in height of the blood flow curve over a period E (s).

Although Greenfield *et al.* (1963) outline the basic method of measuring blood flow using venous occlusion plethysmography, there are various procedural artefacts that might affect the accurate measurement of finger blood flow using venous occlusion plethysmography. Three experiments were conducted to explore the affect of varying the parameters of the venous occlusion measurement method:

1) Multi-channel and single-channel venous occlusion plethysmography for finger blood flow measurement;

   Ascertaining the parameters to use for accurate finger blood flow measurement on multiple fingers using an *HVLab* multi-channel plethysmograph.

2) Comparison between two venous occlusion plethysmographs for finger blood flow measurement;

   Comparing the finger blood flow readings from an *HVLab* multi-channel plethysmograph and from a Digitmatic Medimatic plethysmograph, in order for data collected by both machines to be compared.

A third experiment was conducted to test for the effect of whole-body vibration on finger blood flow;

3) Measurement of peripheral blood flow during whole-body vibration;

It is known that hand-transmitted vibration reduces finger blood flow during and after vibration exposure. It is not known whether prior exposure to whole-body vibration may affect finger blood flow and whether this will need to be controlled in future experiments.

The results of the three experiments should facilitate measurements in future experiments that are accurate, free from measurement artefact and free from confounding effects of previous exposure to vibration.

4.2 EXPERIMENT 1 MULTI-CHANNEL AND SINGLE-CHANNEL VENOUS OCCLUSION PLETHYSMOGRAPHY FOR FINGER BLOOD FLOW MEASUREMENT

4.2.1 Introduction

Blood flow has been used as an indicator of acute local and central changes consequent upon exposure to various types of hand-transmitted vibration (e.g. Bovenzi *et al.,* 1995, 1998, 1999, 2000; Bovenzi and Griffin, 1997), but standardised methods of measuring blood flow on multiple fingers have not been fully established. There are various artefacts that might affect measurements and their interpretation and several independent variables that may influence measurements, for example the occlusion pressure, differences between fingers, number of occluded fingers and the location of the measured hand.

Greenfield *et al.* (1963) state that arterial inflow is unaffected over a wide range of sub-diastolic pressures and that pressure in the distal arteries is unaffected when a cuff is inflated at any sub-diastolic pressure. A further study has reported that the basal critical closing pressure for digital arteries in thermo-neutral conditions varies between subjects from about 10 to 60 mmHg (Bovenzi and Griffin, 1997). Lindsell (1995) found simultaneous measurement on one or five digits did not affect finger systolic blood pressure measurements when using an *HVLab* multi-channel plethysmograph. It is not known whether blood flow varies between fingers or whether the simultaneous measurement on more than one finger affects measurements when using venous occlusion plethysmography.

The location of the measurement site relative to the heart might affect the measured blood flow. Greenfield *et al.* (1963) measured blood flow in a large limb above heart

level to encourage free venous drainage. Greenstein and Kester (1992) measured blood flow above the level of the heart with the subject supine, whereas some others have measured blood flow with the subject in a seated position. Bovenzi and Griffin (1997) measured finger blood flow at different hand heights above the heart with seated subjects in order to establish a pressure-flow relation in the fingers.

The purpose of Experiment 1 was to investigate factors that may affect the measurement of finger blood flow (FBF).

Experiment 1 consisted of three separate smaller experiments conducted to: (i) compare simultaneous measurements on five fingers with measurement on one finger alone, (ii) investigate the effect of different cuff inflation pressures on results, (iii) investigate the differences between digits, and (iv) investigate the effect of elevating the hand relative to the heart.

The hypotheses were:

- Simultaneous measurements on five fingers will not produce a different FBF from measurements on a single finger;
- There will be no difference in finger blood flow between the five fingers;
- Varying the cuff occlusion pressure will affect the reliability of FBF measurements;
- Varying the height of the hand relative to the heart will affect FBF measurements.

4.2.2 Method

4.2.2.1 Subjects

Subjects attended one session during which finger blood flow was measured using both methods. Twelve healthy male subjects were selected from University staff and student populations. Subjects ranged in age from 20 to 45 years. Subjects were non-smokers, not taking any medication at the time of the experiment, had no prior occupational exposure to hand-transmitted vibration and had not consumed tea or coffee within an hour prior to testing.

4.2.2.2 Experimental Conditions

The experiment was conducted in a quiet room at 25°C (±2°C). Subjects, who were acclimatised for 10 minutes at room temperature before commencing the test, lay supine on a clinic bench with the left arm supported at heart level (except where

specified). Watches and jewellery were removed to avoid restricting blood flow. Finger skin temperature was measured at the start of each part of the experiment.

4.2.2.3 Equipment

The *HVLab* (ISVR, University of Southampton) plethysmograph was employed. Throughout the experiment, the pneumatic occlusion pressure was achieved using the same cuffs and the same plastic tubes, and the lengths of tubing between machine and hand (83 cm) were kept constant.

4.2.2.4 Design and Procedure

The Experiment 1 was divided into three parts.

Experiment 1 Part One: Comparison of simultaneous measurements on five fingers with measurement on one finger

Finger blood flow was measured on the middle left finger in two conditions: with the HVLab plethysmograph on the middle left finger in two conditions: (ia) when all five fingers on the left hand were occluded, and (bii) when only the middle left finger was occluded. The order of testing was balanced such that six subjects were tested first with five fingers occluded and six subjects commenced with one finger occluded.

When measuring on a single finger, a single cuff and a single strain gauge were used on the left hand and the other four cuffs were placed on the right hand. Five consecutive finger blood flow measurements were obtained, with a pressure of 60 mmHg applied for 8 seconds.

Experiment 1 Part Two: Cuff inflation pressure

Using the HVLab plethysmograph, finger blood flow was measured simultaneously on all fingers of the left hand with nine cuff occlusion pressures. The order of presenting the occlusion pressures was randomised. Five consecutive finger blood flow measurements were obtained, with a pressure applied for 8 seconds at: 30, 40, 50, 60, 70, 80, 90, or 100 mmHg.

Experiment 1 Part Three: Elevating the hand relative to the heart

Using the HVLab plethysmograph, the finger blood flow was measured simultaneously on all fingers of the left hand with the hand level with the heart, 250 mm below the heart and 250 mm above the heart. Five consecutive finger blood flow measurements were obtained, with a pressure of 60 mmHg applied for 8 seconds.

4.2.3 Statistical Methods

Data analysis was performed with the software package SPSS (version 10.0). The data were summarised with the median as a measure of central tendency and the inter-quartile range as a measure of dispersion. Non-parametric tests (Friedman test for k-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed in the statistical analysis.

4.2.4 Results

Part One: Comparison of simultaneous measurements on five fingers with measurement on one finger

There was no significant difference between finger blood flow measurements on the middle finger when measured alone or when measured at the same time as the other four fingers on the same hand (p=0.937). The median (IQR) measures of finger blood flow were 0.589 ml/100ml/sec (0.462) when measuring on only one finger and 0.503ml/100ml/sec (0.404) when measuring on all five fingers.

Part Two: Cuff inflation pressure

° In all five fingers, changes in occlusion pressure resulted in a significant variation in the indicated finger blood flow ($p<0.001$; Friedman); see Table 4-1.

Table 4-1 Median (inter-quartile range) of finger blood flow (ml/100ml/sec) indicated for each finger at each occlusion pressure.

Occlusion Pressure (mmHg)	Thumb	Index	Middle	Ring	Little
30	0.15 (0.09)	0.07 (0.06)	0.13 (0.09)	0.11 (0.16)	0.05 (0.08)
40	0.25 (0.25)	0.15 (0.14)	0.25 (0.28)	0.16 (0.11)	0.14 (0.16)
50	0.41 (0.33)	0.36 (0.24)	0.55 (0.23)	0.39 (0.29)	0.35 (0.18)
60	0.50 (0.30)	0.41 (0.31)	0.61 (0.50)	0.37 (0.29)	0.30 (0.33)
70	0.66 (0.50)	0.67 (0.63)	0.96 (0.53)	0.66 (0.43)	0.69 (0.39)
80	0.65 (0.31)	0.70 (0.40)	0.89 (0.53)	0.80 (0.41)	0.65 (0.34)
90	0.77 (0.33)	0.76 (0.40)	0.82 (0.64)	0.70 (0.57)	0.56 (0.32)
100	0.79 (0.57)	0.93 (0.55)	0.86 (0.40)	0.82 (0.52)	0.67 (0.49)

On each finger, the statistical significance of the differences between measures for all pairs of occlusion pressures were determined ($p<0.05$; Wilcoxon).

Occlusion pressures below about 60 mmHg probably resulted in some erroneous indications of finger blood flow.

Table 4-2 shows that there were no significant differences between blood flow measured with 70, 80, 90 and 100 mmHg occlusion pressures. In most fingers there was a significant difference between indicated blood flow measured at 30 and 40 mmHg and the blood flow indicated when using higher occlusion pressures . This is because some of the lower pressures were insufficient to produce venous occlusion: the indicated blood flow measured on some subjects with low pressures was not indicative of true blood flow. Of the traces obtained with 30 mmHg occlusion pressure, 58% showed a pulse that overpowered the inflow trace or an artefact following application of the pressure that was large relative to any inflow. It appeared that 33% of measurements at these pressures were of a typical shape while 8% showed no inflow or clear pulse or were erratic.

Table 4-2 Sum of significant differences between occlusion pressures (mmHg) over the five fingers (x = statistically significant difference between finger blood flows at the two occlusion pressures, one cross per finger, $p < 0.05$, Wilcoxon)

Occlusion Pressure (mmHg)	30	40	50	60	70	80	90	100
100	xxxx	xxxxx	xxxx	xx				
90	xxxx	xxxxx	xxxx	xx				
80	xxxx	xxxxx	xxxx	xxx				
70	xxxx	xxxxx	xx	xxxx				
60	xxxx	xxxxx			xxxx	xxx	xx	xx
50	xxxx	xxxxx			xx	xxxx	xxxx	xxxx
40	xxx		xxxxx	xxxxx	xxxxx	xxxxx	xxxx	xxxxx
30		xxx	xxxx	xxxxx	xxxx	xxxx	xxxx	xxxx

At 40 mmHg, traces were of a typical shape, showing a smooth arterial inflow followed by a levelling and the appearance of a pulse. At 70 to 100 mmHg the traces also showed a smooth arterial flow, with no jump.

There were no significant differences between blood flows measured on different fingers (see Table 4-1) (except at 50 mmHg; p=0.019; Friedman,) where the middle finger gave a higher blood flow than the index finger (p=0.004) and the little finger gave a lower blood flow than the middle finger (p=0.023).

Table 4-3 Median (inter-quartile range) of finger blood flow (ml/100ml/sec) for each finger at three elevations of the hand.

	250 mm above heart	Level with heart	250 mm below heart
Finger 1	0.76 (0.52)	0.56 (0.34)	0.14 (0.09)
Finger 2	0.44 (0.54)	0.48 (0.27)	0.14 (0.14)
Finger 3	0.48 (0.29)	0.58 (0.68)	0.15 (0.07)
Finger 4	0.44 (0.37)	0.53 (0.39)	0.14 (0.09)
Finger 5	0.53 (0.39)	0.54 (0.46)	0.12 (0.12)

The inter-quartile range in indicated blood flow at 50 mmHg shows less variance, and therefore a stronger measure of central tendency in the index and middle fingers and in the little finger than in the thumb and ring finger (Table 4-1).

The inter-quartile range in the indicated finger blood flow for each finger at 30 mmHg and 40 mmHg showed less variance in scores than at 60 mmHg (Table 4-1). The variance then increased as pressure increased.

Part Three: Hand height relative to the heart

All five fingers showed significant changes in blood flow with change in elevation relative to the heart ($p < 0.001$; Friedman)(Table 4-3).

There were no significant differences within any finger between finger blood flow at heart level and 250 mm above the heart ($p>0.05$; Wilcoxon), but there were significant reductions in blood flow in each finger when the hand was lowered to 250 mm below heart level ($p<0.02$).

4.2.5 Discussion

There were no significant differences between five successive measures with the plethysmograph. This suggests that there is no learning, habituation or adaptation during a set of rapidly repeated measurements of blood flow.

The absence of an affect of occluding blood flow in other fingers on the finger blood flow measured in the middle finger indicates that it is possible to use the multi-channel plethysmograph to simultaneously measure the blood flow of all five fingers of the same hand.

Changing the occlusion pressure produced a significant difference in the indicated finger blood flow within each finger. In order of sensitivity to occlusion pressures, the most sensitive digit was the ring finger, followed by the little finger and the index finger, with the thumb and middle finger least sensitive (Table 4-1). This seems

reasonable considering the inherent physiological differences in blood flow between fingers.

The occlusion pressure normally used for measuring blood flow is a sub-diastolic pressure of 60 mmHg for all fingers. This pressure gave significantly different FBF measurements from those at 50 mmHg in all fingers and from those at 70 mmHg in the thumb, index and middle fingers. This is not consistent with the suggestion from Greenfield *et al.* (1963) that occlusion pressure is not critical, provided it is a sub-diastolic pressure. When comparing the blood flow in each finger at each pressure, the only significant difference between fingers was found at 50 mmHg. It seems possible that the most sensitive range for occlusion was within the 50 to 70 mmHg range.

Although significant differences were found between 30 mmHg and all other occlusion pressures, this could be due to unreliable traces. If it is assumed that subject's finger blood flow did not change with the different pressures, it was the ability to measure the blood flow that altered. With the occlusion pressures at about 80 mmHg (and above) the pressure may not be sub-systolic in some subjects; the increased range in median blood flow was indicative of increased individual differences.

Hand elevation affected finger blood flow in a consistent manner across all fingers: blood flow was lower with the hand below heart level, consistent with the recommendations of Greenfield *et al.* (1963) that sensitivity of readings is dependent on adequate venous drainage. The findings suggest that the hand should be at or above heart level. Further research should investigate whether it is necessary for a subject to be supine during the measurement of finger blood flow.

Although venous occlusion plethysmography may provide useful indications of changes in finger blood flow, it is not clear how accurately the indicated measures of blood flow reflect absolute measures that may be indicated by other methods. It may even be expected that there could be appreciable differences between absolute measures of blood flow indicated by different venous occlusion plethysmographs.

4.2.6 Conclusions

There was no significant difference in finger blood flow on the middle finger when occluded singly or occluded with the other four digits of the same hand. Multi-channel venous occlusion seems to be as reliable and as sensitive as single-channel venous occlusion.

Varying the occlusion pressure gave rise to significant changes in the indicated blood flow of each finger. The methods allow the apparent measurement of finger blood flow when the pressure is too low to cause venous occlusion and too high to allow full arterial inflow. The traces provided in these conditions might be mistaken for typical responses and used to calculate a blood flow. Pressures in the range 50 to 70 mmHg seem to result in measurements that may be reliably interpreted as indicative of finger blood flow.

It is necessary to maintain the occluded hand at, or above, heart level; however, small variations in hand elevation above heart level did not affect the indicated blood flow.

4.3 EXPERIMENT 2: COMPARISON BETWEEN TWO VENOUS OCCLUSION PLETHYSMOGRAPHS FOR FINGER BLOOD FLOW MEASUREMENT

4.3.1 Introduction

Single channel plethysmographs designed for measuring blood flow in limbs, such as at the arm or calf, have been adapted for use on the finger. These have been used as indicators of acute local and central changes in finger blood flow consequent upon exposure to various types of hand-transmitted vibration (e.g. Bovenzi *et al.,* 1995, 1998, 1999, 2000; Bovenzi and Griffin, 1997).

The standardisation of the test procedure and the repeatability of methods between different apparatus are important to allow comparison of results. Knowledge of any differences between apparatus may allow the rescaling of results from one machine to another. It will also help develop a calibration procedure.

Different methods of assessing peripheral blood flow should not be compared (Greenfield *et al.,* 1963), even when measuring at the same location and at the same time, as no two methods for measuring peripheral blood flow measure the same aspect.

There are various procedural artefacts that might affect the accurate measurement of finger blood flow using venous occlusion plethysmography. As experiment one showed, these include the occlusion pressure, number of occluded fingers, the location of the measured hand and cuff and strain gauge size. Brengelmann *et al.*, (1986) state that tissue compressibility relative to the size of the digit being measured may also affect the accuracy of measurement. Other variables that can affect the

interpretation of measurements of blood flow include physiological differences between fingers and the positioning of the blood inflow slope on the blood flow trace.

If these variables are controlled, it is assumed that the results from one apparatus may be comparable to those recorded by another. Otherwise, there are further variables requiring compensation to be discovered.

The purpose of this study was to investigate factors that may affect the measurement of finger blood flow (FBF) by comparing finger blood flow measurements with two different venous occlusion plethysmographs. The main known difference between the two plethysmographs was that one (*HVLab* plethysmograph) used a four terminal system for connecting the strain gauges so as to ensure that resistances in the cables and connectors did not affect the strain measurements.

A two-part experiment was conducted to compare blood flows obtained with the two plethysmographs. In the first experiment, before the difference in cable compensation was known, it was hypothesised that the finger blood flow measurements would not differ between the two plethysmographs. In the second experiment, the cable resistance to the strain gauge was measured: it was hypothesised that after compensating for cable resistance, finger blood flow measurements would not differ between the two plethysmographs.

4.3.2 Method

4.3.2.1 Equipment

Two different plethysmographs were employed: Digitmatic DM2000 (Medimatic A/S, Copenhagen) and *HVLab* (ISVR, University of Southampton).

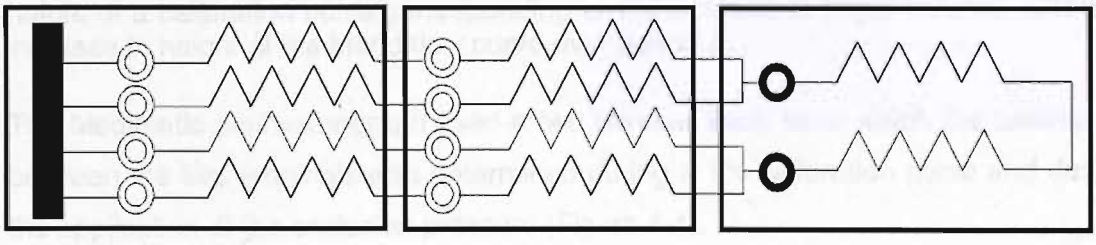
Two different resistance mercury-in-silastic strain gauges were used. These can be described in terms of size, cable resistance and gauge resistance. A low resistance strain gauge had a circumference of 38 mm (with internal overlap of 4 to 7 mm), a lead resistance of 0.114 ohms and a mercury-in-silastic gauge unstretched resistance of 0.234 ohms (R_s). A high resistance strain gauge had a circumference of 51 mm (with internal overlap of 4 to 7mm), a lead resistance of 0.099 ohms and a mercury-in-silastic gauge unstretched resistance of 0.271 ohms (R_s). An adapter, which enabled these two 5-pin strain gauges to fit into the 3-pin Medimatic socket, had a resistance of 0.104 ohms (adaptor and cable resistance is R_c).

4.3.2.1.1 HVLab plethysmograph

The *HVLab* plethysmograph was computer-controlled and produced a computer-generated graphical representation of the increase in finger volume over time (Figure 4-1).

Figure 4-1 Change in strain recorded on five fingers following occlusion (60 mmHg occlusion pressure, 8-second occlusion duration)

The slope of the blood flow curve was estimated automatically by the computer from the increase in strain. The experimenter was able to review and adjust the slope if necessary. The computer recorded the increase in blood flow as determined by the blood flow slope. The *HVLab* plethysmograph used a four terminal lead arrangement (Figure 4-2).



Plethysmograph Cable Strain gauge

Figure 4-2 *HVLab* four-terminal lead arrangement showing sections of electronic resistance. Bold circles indicate the points at which resistance is measured.

The four terminal lead arrangement measured the resistance across the strain gauge only. It measured, at this point, both the static stretch around the finger prior to the application of pressure (R_g) and the dynamic (i.e. increasing) stretch of the gauge around the finger during the application of the occlusion pressure (R_g').

The equivalent of *A* (height of calibration pulse) is $R_g/100$ and therefore blood inflow can be calculated from:

$$A_{in}\,(HVLab) = \frac{100R'_g}{(R_g.E)}$$

4.3.2.1.2 Medimatic plethysmograph

The Medimatic plethysmograph provided a paper chart that indicated the increase in finger volume over time at 2.5 mm per second (Figure 4-3).

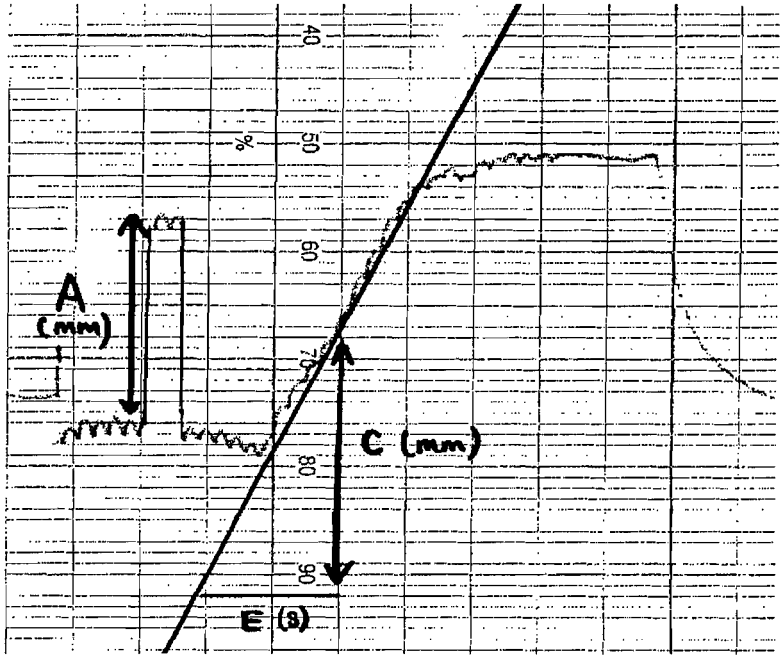
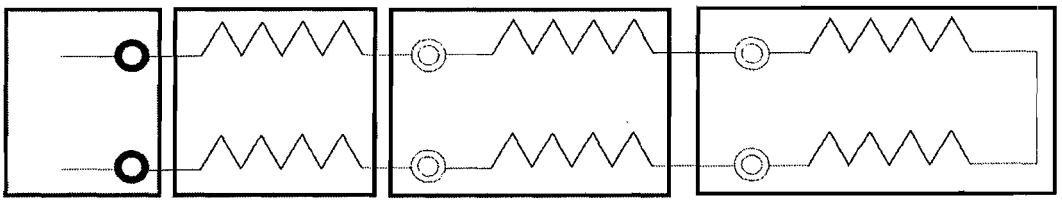


Figure 4-3 Change in strain recorded on one finger following occlusion on the Medimatic (60mmHg occlusion pressure, 8-second occlusion duration (*E*)). *A* is the height of a calibration pulse corresponding to 1% increase in finger volume, *C* is the increase in height of the blood flow curve over period *E*.

The Medimatic plethysmograph used a two terminal lead, from which the resistance between the two terminals was determined during a 1% calibration pulse and during the application of the occlusion pressure (Figure 4-4).



Plethysmograph Adaptor Cable Strain gauge

Figure 4-4 Medimatic two-terminal lead arrangement showing sections of electronic resistance. Bold circles indicate the points at which resistance is measured.

The Medimatic plethysmograph did not appear to measure the resistance of a strain gauge independently of the resistance of the cables and connectors between the strain gauge and the instrument. The height of A was therefore equivalent to $0.01(R_g+R_c)$ where R_c is the additional resistance of the cables and connectors. Hence the estimate of A_{in} given by the Medimatic plethysmograph was equivalent to:

$$A_{in}(DM2000) = \frac{100R'_g}{(R_g + R_c)E}$$

where R'_g is the increase in gauge resistance over period E and R_g represents the resistance of the gauge when it is stretched around the finger. This is slightly greater than the unstretched resistance, so the use of the unstretched resistance in the above expression will lead to an overestimate of A_{in}. The difference between the stretched and unstretched resistances is determined by the circumference of the finger relative to that of the gauge, and varies between subjects.

4.3.2.1.3 Comparison of the characteristics of the Medimatic and HVLab plethysmographs

Both the Medimatic plethysmograph and the *HVLab* plethysmograph estimated strain gauge resistance by measuring the voltage across the terminals with constant current excitation. As explained above, the Medimatic used a two-terminal arrangement, so measurements of strain gauge resistance included the resistance of the cable joining the strain gauge to the instrument. The *HVLab* plethysmograph used a four-terminal arrangement making it possible to directly measure the resistance across the strain gauge, eliminating error due to cable resistance. Typical changes in resistance measured during venous occlusion of the finger were in the range 0.1 to 2% of the resistance of the strain gauge.

Other differences between the two plethysmographs were that the *HVLab* system allowed simultaneous measurements of blood flow at five locations; it was computer-controlled and stored individual blood flow curves as well as individual and mean slopes within the computer. It compensated for strain gauge cable resistance and the cuff inflation pressure compensated for the volume of air in the tubing and cuffs. The Medimatic plethysmograph provided a paper record of results; it allowed simultaneous measurements at two locations; did not compensate for strain gauge cable resistance, and did not easily allow accurate control of air pressure since it did not compensate for the volume of air in the tubing and cuffs.

Table 4-4 Specifications of the *HVLab* plethysmograph (Lewis, 1996) and the Medimatic plethysmograph

Software selected parameters	Medimatic	*HVLab*
Number of test fingers	1-2	1-5
Inflation Pressure	0-300mmHg	0-300 mmHg
Fixed parameters	Medimatic	*HVLab*
Cuff inflation rate	Unknown	>300 mmHg s^{-1}
Strain gauge resistance range High resistance gauge: Low resistance gauge:	N/A	0.25 – 0.8 ohm
Data sampling rate	Analogue	18 samples s^{-1}

4.3.2.2 Calibration

The strains measured by the two plethysmographs were investigated by connecting two dummy electrical resistors: a resistance of 0.5 ohms in parallel with a 50 ohm resistor, and a resistor of 10 ohms in parallel with a 100 ohm resistor. The occlusion pressures were calibrated by measuring the pressure at the cuff with a manometer in comparison with the pressure supplied by the plethysmograph.

Before each finger blood flow measurement, the resistance of the strain gauge was measured before venous occlusion. Venous occlusion was then applied by instantly inflating the pneumatic cuffs to the required pressure of 60 mmHg. The subsequent rise in volume of the fingertip was monitored from the changing resistance of the strain gauge over a period of a few seconds. The finger blood flow was calculated from graphical records of the changing resistance of the strain gauge using the method suggested by Greenfield *et al.* (1963).

4.3.2.3 Subjects

Subjects attended one session during which finger blood flow was measured using both methods. Twelve healthy male subjects were selected from University staff and student populations. Subjects ranged in age from 20 to 45 years. Subjects were non-smokers, not taking any medication at the time of the experiment and had no prior occupational exposure to hand-transmitted vibration.

4.3.2.4 Experimental Conditions

The experiments were conducted in a quiet room at 25°C (±2°C). Subjects were acclimatised for 10 minutes at room temperature before commencing the test. The subject lay supine on a clinic bench with the left arm supported at heart level. Watches and jewellery were removed to avoid restricting blood flow. Finger skin temperature was measured at the start of the experiment. Subjects had not drunk coffee or tea, or smoked cigarettes for two hours prior to testing. Subjects had not been exposed to vibration for two hours prior to testing.

4.3.2.5 Experimental Design

Experiment 2 consisted to two smaller experiments, Part A and Part B. Twelve subjects participated in Part A and Part B in which finger blood flow was measured on one finger using both plethysmographs. In Part A and Part B, the order of testing was balanced such that six subjects were tested first with the Medimatic plethysmograph and six subjects commenced with the *HVLab* plethysmograph.

One air cuff and one strain gauge were placed on the middle finger of the left hand. In the Part A of Experiment 2, the strain gauge with the best fit around the finger was chosen for each subject (Greenfield *et al.*, 1963). The air cuff on the left hand was connected in series to four other cuffs that were placed around the digits of the contralateral hand. In rapid succession, five consecutive finger blood flow measurements were obtained using each machine, with a pressure of 60 mmHg applied for 10 seconds in Part A and 8 seconds in Part B.

Five good traces of arterial inflow were obtained from each subject for each measurement condition and the median value was calculated. The finger blood flow measurements were expressed as ml/100 ml/sec.

For all measurements with both systems the pneumatic occlusion pressure was achieved using the same cuffs and the same plastic tubes, with the length of tubing between machine and cuff (83 cm) kept constant. The strain gauges and cuffs were not moved on the fingers between measurements on the two plethysmographs.

In Part B of Experiment 2, finger blood flow was determined simultaneously in five successive measurements at two sites using both plethysmographs. On the right middle finger a strain gauge with low strain gauge resistance (0.234 ohms) was used. On the right thumb a strain gauge with high resistance (0.271 ohms) was used. The same two strain gauges were used on all subjects. The order of testing between machines was again balanced.

Part A of Experiment 2 used a variety of strain gauges, whatever was of an appropriate size for the subject. The second experiment used two strain gauges with known resistances to allow the estimation of scaling factors required to compare measurements with the Medimatic and *HVLab* plethysmographs, and allow compensation for the cable resistance in the Medimatic plethysmograph.

In Part B of Experiment 2, for both strain gauges, a scaling factor was applied to strain indicated by the Medimatic plethysmograph so as to predict the strain as measured by the *HVLab* plethysmograph:

$$A_{in}\ (HVLab) \equiv \frac{R_g + R_c}{R_g} A_{in}\,(\mathrm{DM2000})$$

where R_g represents the resistance of the gauge with static stretch around the finger and R_c is the resistance of the cables and connectors. As R_g was unknown, it was replaced by the unstretched resistance of the strain gauge (R_s), although it is acknowledged that this was an estimate and the true value depended upon finger size:

$$A_{in}\ (HVLab) \equiv \frac{R_s + R_c}{R_s} A_{in}\,(\mathrm{DM2000})$$

4.3.3 Statistical Methods

Data analysis was performed with the software package SPSS (version 10.0). The data were summarised with the median as a measure of central tendency and the inter-quartile range as a measure of dispersion. Non-parametric tests (Spearman rank correlation, Friedman test for *k*-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed in the statistical analysis.

4.3.4 Results

4.3.4.1 Experiment 2 Part A

Table 4-5 shows the median (interquartile range) of finger blood flow measured with the *HVLab* and Medimatic plethysmographs with mixed strain gauges. The

Medimatic plethysmograph gave consistently lower finger blood flow values than the *HVLab* plethysmograph.

Table 4-5 Median (inter-quartile range) of finger blood flow (ml/100ml/s) with *HVLab* and Medimatic plethysmographs in Part A of Experiment 2 with mixed strain gauges over subjects.

Subject	*HVLab*	Medimatic
1	0.57 (0.23)	0.14 (0.13)
2	0.22 (0.04)	0.31 (0.25)
3	0.06 (0.05)	0.07 (0.06)
4	0.37 (0.17)	0.16 (0.14)
5	0.66 (0.33)	0.19 (0.18)
6	0.30 (0.20)	0.15 (0.08)
7	0.23 (0.50)	0.15 (0.20)
8	0.22 (0.26)	0.18 (0.09)
9	0.49 (0.29)	0.14 (0.23)
10	0.61 (0.22)	0.09 (0.07)
11	0.46 (0.09)	0.13 (0.10)
12	0.22 (0.31)	0.17 (0.08)
Median	0.34 (0.23)	0.15 (0.12)

Figure 4-5 shows the relationships between blood flows indicated by the two plethysmographs. Not only were the blood flow measures different, there was no correlation between the two measures (p=0.73; Spearman rank correlation). It is not clear whether the difference between the two plethysmographs can be accounted for by the uncompensated lead resistance in the Medimatic plethysmograph, or from systematic errors in the positioning of the blood flow slopes between the two machines, or errors introduced by other factors, including intra-subject variability in blood flow.

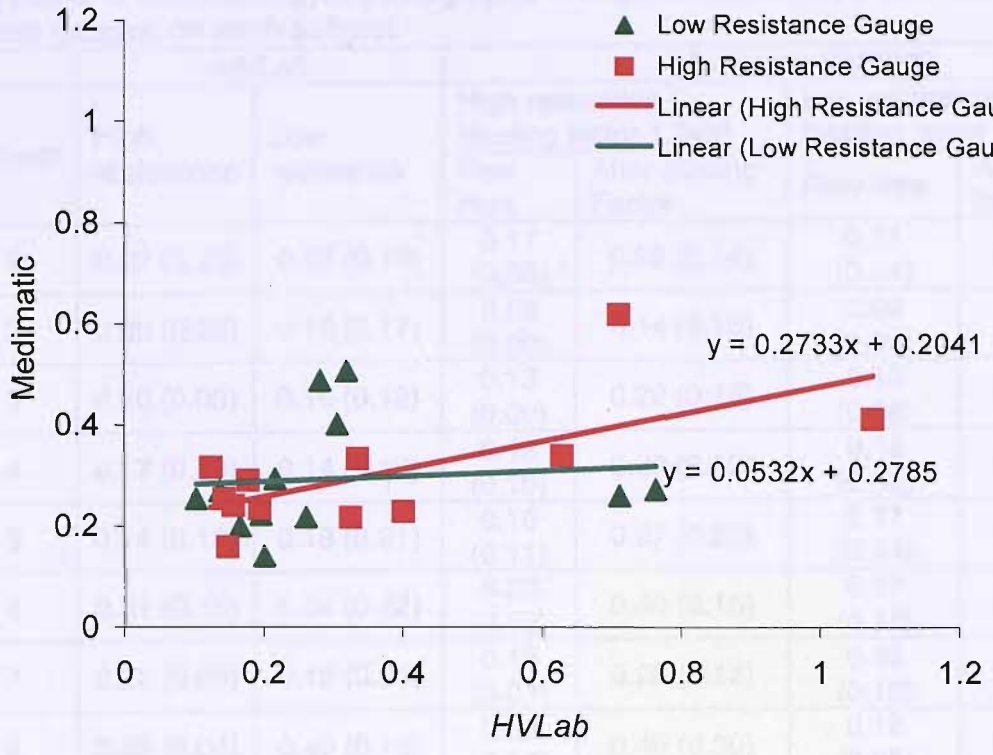


Figure 4-5 Median finger blood flows on each subject using the *HVLab* and Medimatic plethysmographs

4.3.4.2 Experiment 2 Part B

In the Part B of Experiment 2, the same strain gauges were used for all subjects so as to control the resistance of the strain gauge and the resistance of the cable (and strain gauge cable adapter used with the Medimatic).

For each of the four measurements (two locations and two plethysmographs), there were again no significant differences within subjects over the five successive measures of finger blood flow (p>0.4; Friedman).

The finger blood flows directly indicated by the two plethysmographs (without compensation for cable resistance) are shown in Table 4-6 and Figure 4-6.

Table 4-6 Median (inter-quartile range) of finger blood flow (ml/100ml/s) with *HVLab* and Medimatic plethysmographs in Experiment 2 Part B with the same strain gauges on each subject.

	HVLab		Medimatic DM2000			
Subject	High resistance	Low resistance	High resistance [scaling factor 1.749]		Low resistance [scaling factor 1.932]	
			Raw data	After Scaling Factor	Raw data	After scaling factor
1	0.22 (0.23)	0.33 (0.10)	0.17 (0.08)	0.29 (0.14)	0.11 (0.04)	0.22 (0.07)
2	0.20 (0.25)	0.15 (0.17)	0.08 (0.09)	0.14 (0.15)	0.08 (0.03)	0.16(0.05)
3	0.20 (0.09)	0.16 (0.12)	0.13 (0.09)	0.22 (0.16)	0.13 (0.06)	0.24 (0.11)
4	0.17 (0.10)	0.14 (0.10)	0.12 (0.10)	0.20 (0.18)	0.13 (0.02)	0.26 (0.04)
5	0.14 (0.12)	0.18 (0.21)	0.16 (0.11)	0.27 (0.20)	0.17 (0.14)	0.33 (0.26)
6	0.31 (0.15)	0.34 (0.22)	0.23 (0.08)	0.40 (0.15)	0.17 (0.18)	0.33 (0.35)
7	0.26 (0.08)	0.12 (0.03)	0.13 (0.07)	0.22 (0.13)	0.16 (0.13)	0.32 (0.25)
8	0.28 (0.04)	0.40 (0.15)	0.28 (0.17)	0.49 (0.30)	0.12 (0.05)	0.23 (0.10)
9	0.10 (0.05)	0.19 (0.10)	0.15 (0.04)	0.26 (0.07)	0.12 (0.13)	0.24 (0.25)
10	0.76 (0.52)	0.63 (0.29)	0.16 (0.04)	0.27 (0.06)	0.18 (0.11)	0.34 (0.22)
11	1.08 (0.09)	0.32 (0.09)	0.15 (0.08)	0.26 (0.15)	0.32 (0.17)	0.62 (0.33)
12	0.71 (0.30)	0.71 (0.36)	0.29 (0.02)	0.51 (0.28)	0.21 (0.05)	0.41 (0.10)
Median	0.24 (0.11)	0.26 (0.14)	0.15 (0.08)	0.27 (0.15)	0.15 (0.09)	0.29 (0.16)

The readings from the Medimatic plethysmograph were corrected for the cable resistance using the scaling factors as described above (Table 4-6). This increased the measured blood flows by a factor of approximately 1.75 with the high resistance strain gauge and 1.93 with the low resistance strain gauge; the increase depends on the resistance of the strain gauge and cable used. After scaling, the median blood flows on each plethysmograph were similar (Table 4-6): the low resistance strain gauge *HVLab* median was 0.257 ml/100ml/sec whilst the Medimatic median was 0.286 ml/100ml/sec; (p=0.754, Wilcoxon); for the high resistance strain gauge the *HVLab* median was 0.239ml/100ml/sec whereas the Medimatic median was 0.266 ml/100ml/sec (p=1.0).

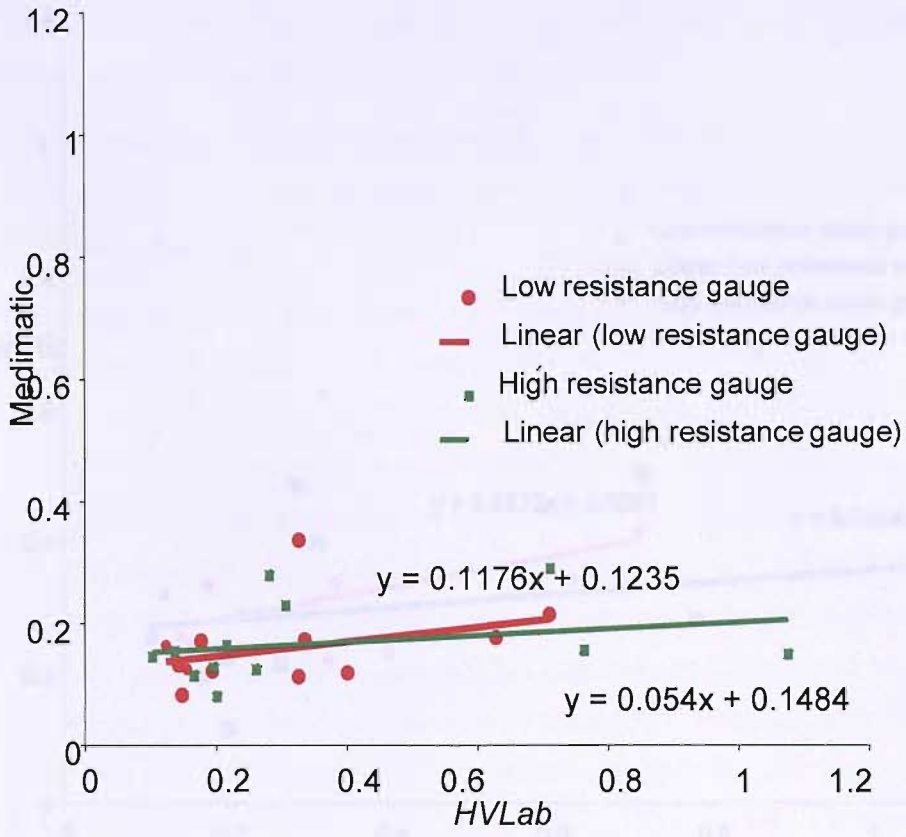


Figure 4-6 Median uncorrected finger blood flow for each subject, using low resistance and high resistance strain gauges on both plethysmographs.

Figure 4-7 shows the correlation between the indicated *HVLab* blood flow readings and the scaled Medimatic readings. There was a marginally significant correlation between measures obtained using the two plethysmographs with the high resistance strain gauge (p=0.095, Spearman rank correlation) but not with the low resistance strain gauge (p=0.245). With the high resistance strain gauge, the scaling factor changed the regression from $y = 0.054x + 0.148$ to $y = 0.094x + 0.260$. With the low resistance strain gauge, the scaling factor changed the regression from $y = 0.118x + 0.124$ to $y = 0.227x + 0.239$. A unity slope would be expected if there were no systematic differences between the two sets of measures.

The inter-quartile range (IQR) of the five measures of blood flow in each subject was calculated for each plethysmograph and both strain gauges, using the rescaled Medimatic data. The median inter-quartile range for the *HVLab* plethysmograph was 0.137 with the low resistance strain gauge and 0.107 with the high resistance strain gauge. The median inter-quartile range for the Medimatic plethysmograph was 0.164 with the low resistance strain gauge and 0.149 with the high resistance strain gauge.

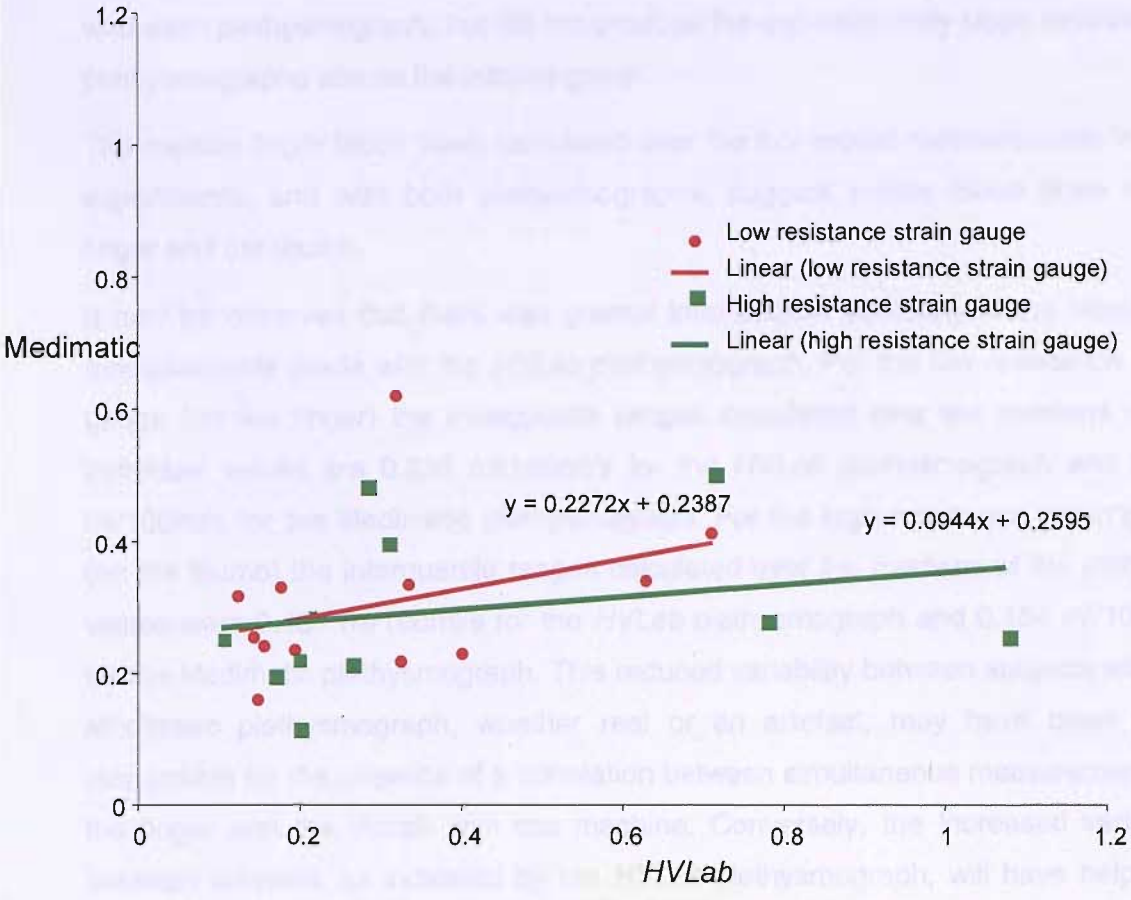


Figure 4-7 Comparison between raw *HVLab* indications of finger blood flow and scaled Medimatic measures of finger blood flow

The two simultaneous measures of blood flow on the *HVLab* plethysmograph (on the thumb with the high resistance strain gauge and on the middle finger with the low resistance strain gauge) were correlated (p=0.036 Spearman rank correlation). However, these two measures were not correlated on the Medimatic plethysmograph (p=0.286).

4.3.5 Discussion

There were no significant differences within subjects between the five successive measures with either the Medimatic or the *HVLab* plethysmograph. This suggests that there was no learning, habituation or adaptation during a set of rapidly repeated measurements of finger blood flow.

The median uncorrected finger blood flows indicated by the Medimatic plethysmograph were significantly less than those measured with the *HVLab* plethysmograph in both parts of Experiment 2. In Part B, scaling the Medimatic data to allow for the cable resistance almost equalised the median blood flows measured

with each plethysmograph, but did not produce the expected unity slope between the plethysmographs across the subject group.

The median finger blood flows calculated over the five repeat measurements in both experiments, and with both plethysmographs, suggest similar blood flows in the finger and the thumb.

It may be observed that there was greater inter-subject variability in the blood flow measurements made with the *HVLab* plethysmograph. For the low resistance strain gauge (on the finger) the interquartile ranges calculated over the medians of the individual values are 0.235 ml/100ml/s for the *HVLab* plethysmograph and 0.107 ml/100ml/s for the Medimatic plethysmograph. For the high resistance strain gauge (on the thumb) the interquartile ranges calculated over the medians of the individual values were 0.437 ml/100ml/s for the *HVLab* plethysmograph and 0.154 ml/100ml/s for the Medimatic plethysmograph. This reduced variability between subjects with the Medimatic plethysmograph, whether real or an artefact, may have been partly responsible for the absence of a correlation between simultaneous measurements on the finger and the thumb with this machine. Conversely, the increased variability between subjects, as indicated by the *HVLab* plethysmograph, will have helped to increase the correlations between simultaneous measurements on the finger and thumb with this machine. The absence of a correlation within subjects and decreased variability between subjects when using the Medimatic plethysmograph will have contributed to the poor correlations between the measures of blood flow indicated by the two machines.

The absence of similar blood flows within subjects when measured with the two plethysmographs, and the inconsistent correlations between measurements obtained with the two plethysmographs, suggests that there may be further variables affecting the measurement of finger blood flow with one of these machines. It is particularly notable that simultaneous measures of blood flow on the finger and on the thumb using the Medimatic plethysmograph were not correlated. This, and the low correlation between blood flow measures obtained with the two plethysmographs might suggest that measures obtained on the Medimatic plethysmograph were more susceptible to influence from extraneous variables. Other potential explanations for differences between plethysmographs include irregularities in the positioning of the finger blood flow curves, differences in the blood flow curve displays affecting interpretation, internal electrical resistance in one of the plethysmographs, the size of strain gauge relative to finger size, intra-subject variability and differences between unstretched and static stretched strain gauge resistance.

The finger blood flows indicated by the Medimatic plethysmograph are comparable to the blood flows reported in previous studies for the same sites using the same method with the same Medimatic plethysmograph in the same laboratory. For example, Bovenzi *et al.* (1998) reported a median blood flow of 7.9 ml/100ml/min (0.13 ml/100ml/s), Bovenzi *et al.* (1995) reported 17.9ml/100ml/min (0.30 ml/100ml/s), and Bovenzi and Griffin (1997) reported 27.6 ml/100ml/min (0.46 ml/100ml/s) and 33.4 ml/100ml/min (0.56 ml/100ml/s). Although the median blood flow measured in this experiment tended to be lower than those in some previous studies, the variation between previous experiments suggest the values found here are reasonably typical. The actual blood flow will depend on many factors. However, a difference between the present and previous data may also have arisen from differences in the interpretation of the blood flow curves. In the present experiments the first 1-second of inflow after occlusion was ignored because it may contain artefacts caused by the pressurisation of the cuff. Additionally, rather than using either the troughs or the peaks in the curve, as in some previous experiments, only the troughs were used here.

4.3.6 Conclusions

The median finger blood flow indicated by the Medimatic plethysmograph was significantly lower than that obtained using the *HVLab* plethysmograph. The difference between the two machines has been partially explained by one machine not allowing for the influence of the resistance of the cables connecting the strain gauges to the plethysmograph. Further study may investigate the differences between plethysmographs within subjects and the low correlation coefficients seen between some measures.

4.4 EXPERIMENT 3 MEASUREMENT OF PERIPHERAL BLOOD FLOW DURING WHOLE-BODY VIBRATION

An experiment was conducted to test whether whole-body vibration exposure may produce a reduction in peripheral blood flow. Subjects are not exposed to hand-transmitted vibration prior to measurement of finger blood flow as hand-transmitted vibration has an effect on peripheral blood flow. It is not known if exposure to whole-body vibration may also have some affect on the peripheral blood flow.

Ten healthy male subjects were exposed to three conditions of whole-body vertical vibration: 8 Hz at 1 ms^{-2} r.m.s., 63 Hz at 4 ms^{-2} r.m.s. and a control condition with no vibration. Finger and toe blood flow and finger skin temperature were measured during 20 minute's acclimatisation, during 17 minutes of vibration exposure and

during 40 minutes of recovery. With few exceptions, measures before exposure, during exposure and during recovery, showed no pattern of consistent or significant differences in blood flow between the three vibration conditions. In contrast with the responses elicited by hand-transmitted vibration, any acute effects of whole-body vibration on digital blood flow were mild and transient.

Appendix B contains the full text of the study.

4.5 IMPLICATIONS FOR THE THESIS

The three experiments have identified further variables that may affect the measurement of finger blood flow and need to be controlled in future experiments.

Multi-channel venous occlusion seems to give similar measurements of finger blood flow as single-channel venous occlusion.

In addition to the variables outlined by Greenfield *et al.* (1963), in future experiments variables that will be controlled are:

1) Occlusion pressure: pressures in the range 50 to 70 mmHg seem to result in measurements that may be reliably interpreted as indicative of finger blood flow.

2) Height of hand: it is necessary to maintain the occluded hand at, or above, heart level; however, small variations in hand elevation above heart level will not affect the indicated blood flow.

3) Strain gauge size: for each subject the correct size strain gauge will be selected. The same gauge will be used by that subject throughout an experiment, where possible.

4) Prior exposure to vibration: subjects will be asked to avoid hand-transmitted vibration for 2 hours prior to experimental testing. Subjects will not have to avoid whole-body vibration exposure prior to finger blood flow measurement.

The difference between the two plethysmographs has been partially explained by one machine not allowing for the influence of the resistance of the cables connecting the strain gauges to the plethysmograph.

The *HVLab* plethysmograph will be used in future experiments to measure finger blood flow on multiple fingers. Data collected using the Medimatic plethysmograph will be used as guidance, but will not be directly compared to data obtained using the *HVLab* plethysmograph.

CHAPTER 5

THE EFFECT ON FINGER BLOOD FLOW OF PUSH FORCE TO THE FINGER AND INCREASING VIBRATION MAGNITUDE

5.1 INTRODUCTION

To accurately predict the vascular response to vibration it is necessary to better understand the effects of vibration frequency and vibration magnitude on finger blood flow.

Experimental studies have found that finger blood flow during exposure to 125 Hz vibration decreased with increasing vibration magnitude, in the range of 5.5 and 62 ms^{-2} r.m.s. (Bovenzi *et al.*, 1999). At frequencies between 31.5 and 250 Hz, with the same frequency-weighted acceleration magnitude of 5.5 ms^{-2} r.m.s., there were no significant differences between reductions in finger blood flow during vibration exposure (Bovenzi *et al.*, 2000). At 125 Hz Welsh (1980) found a stronger reduction in flow than at other frequencies with constant displacement amplitude.

In previous studies, there has been vasoconstriction in the fingers of both the exposed and the unexposed hand during vibration, but with a stronger vasoconstriction in the exposed hand than in the unexposed hand (Bovenzi and Griffin 1997; Bovenzi *et al.*, 1998, 1999, 2000, 2001). This is consistent with vibration inducing a centrally mediated reduction in flow and a locally mediated vasoconstriction in the exposed hand (Bovenzi *et al.*, 1999).

Immediately after vibration exposure, strong vasodilation in the exposed finger has been reported, compared to blood flow during vibration (Bovenzi and Griffin 1997; Bovenzi *et al.*, 1998, 1999, 2000, 2001). After vibration of 44, 62 and 88 ms^{-2} r.m.s. at 125 Hz, a weak increase in finger blood flow in the unexposed hand has been reported (Bovenzi *et al.*, 1999, 2001).

Fifteen to 30 minutes after vibration exposure, a return of vasoconstriction in both hands has been reported (Bovenzi and Griffin 1997; Bovenzi *et al.*, 1998, 1999, 2000, 2001). The strength of this vasoconstriction seems to be dependent on the frequency of vibration (Bovenzi *et al.*, 2001) as well as the duration and the magnitude of the vibration (Bovenzi *et al.*, 1998, 1999). Vasoconstriction was

stronger in the exposed finger than in the non-vibrated finger (Bovenzi *et al.*, 1998, 1999). With energy-equivalent combinations of different magnitudes and durations of vibration the reduction in finger blood flow after vibration was similar in exposed and unexposed hands (Bovenzi *et al.*, 2001).

It is not clear why the cessation of vibration causes vasodilation that is followed by vasoconstriction in both hands. To predict the vascular response to vibration it may be necessary to understand other interactions between variables influencing vasoconstriction and incorporate these into the dose-response relationship. International Standard 5349 (2001) states that "*forces between the hand and gripping zone should be measured and reported*" and that "*the effects of human exposure to hand-transmitted vibration in working conditions may also be influenced by ... the coupling forces, such as the grip and feed forces, applied by the operator through the hands to the tool or workpiece and the pressure exerted on the skin*". However, Bovenzi *et al.* (1995, 1998) found that a push force of 10 N applied with three fingers had no effect on finger blood flow compared with baseline measurements without force.

Bovenzi *et al.* (2006) found a 2-N push force applied by a finger reduced blood flow in the exposed digit for the 15-minute duration of force, compared to blood flow before the application of force. A 5-N force applied by the finger produced a stronger reduction in blood flow in the exposed digit than the 2-N force. Fingers on the unexposed contralateral hand showed no changes in blood flow during the application of force (Bovenzi *et al.*, 2006).

An objective of this experiment was to investigate a new method of investigating the effects on finger blood flow of vibration and push force.

The two aims of the experiment reported in this chapter were to increase understanding of: (i) the relationship between vibration magnitude and finger blood flow, and (ii) the contribution of push force to the vasoconstriction during vibration exposure.

It was hypothesised that push force would not reduce finger blood flow compared to pre-exposure levels of finger blood flow and that blood flow would decrease with increasing vibration magnitude.

5.2 METHOD

5.2.1 Subjects

Ten healthy male volunteers with a mean (standard deviation) age 28.8 yrs (5.7) participated in the study. All subjects were office workers with no history of regular exposure to vibration and no medical disorders known to influence finger blood flow. The subjects were asked to avoid smoking and caffeine for 2 hours prior to testing and avoid alcohol for 12 hours prior to testing.

5.2.2 Equipment

A Derritron VP4 electrodynamic vibrator provided the vibration and was controlled using a computer-based data acquisition system (*HVLab* version 3.81). A Huntleigh force cell was attached to the vibrator table to measure the downward force exerted by the finger (Figure 5-1).

To monitor vibration, an Entran 233E accelerometer was attached to a metal plate screwed to the top of the force cell. A wooden platform (40 x 12mm) was secured to the top of the metal plate so that the middle phalanx of a subject's right middle finger could be placed on the wooden plate with the remaining fingers suspended in air.

Visual feedback through a force meter allowed subjects to control the application of a push force.

Room temperature was measured using a K-type thermocouple connected to an *HVLab* thermal aesthesiometer that was accurate to 0.5°C. The thermocouple was located close to the heads of the recumbent subjects. Room temperature was controlled by two radiators.

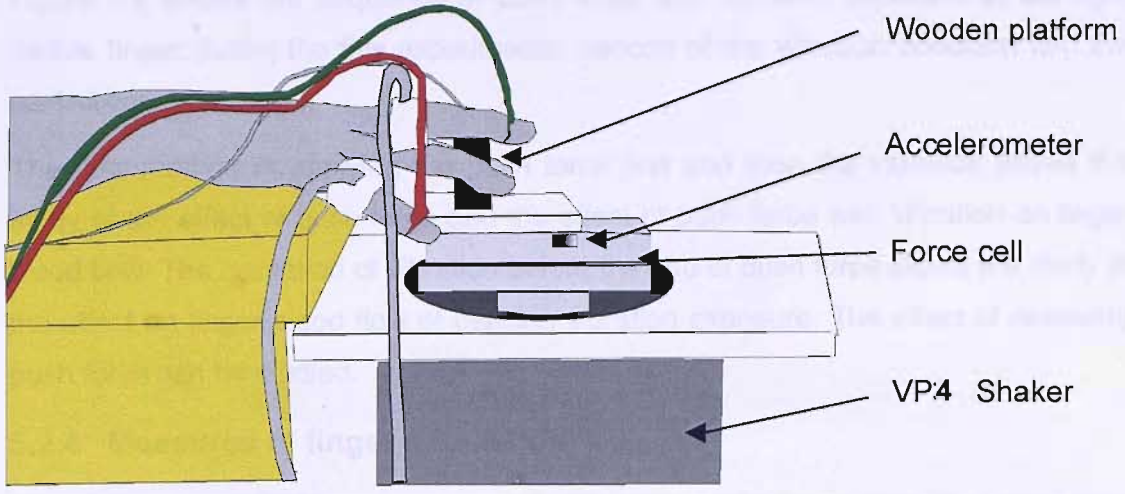


Figure 5-1 Experimental arrangement for generating and measuring the vibration and force at the right middle finger and measuring finger blood flow in the exposed right middle finger and the unexposed right little finger

5.2.3 Experimental conditions

Subjects were asked to apply a 2 N push force.

The vibration at 125 Hz was increased from 0 to 88 ms^{-2} r.m.s. (0 to 11 ms^{-2} r.m.s. frequency-weighted) during a period of 22 minutes. The range of the vibration velocity was 0.0 to 0.11 ms^{-1} r.m.s. A linearly increasing (i.e. ramped) magnitude of vibration was used as this incorporates and extends the range of vibration magnitudes used in previous studies, thereby allowing comparison at specific magnitudes. The vibration frequency of 125 Hz was used as this vibration frequency is known to produce vasoconstriction.

Supine subjects were exposed on separate days to two conditions, each lasting 62 minutes. A vibration condition consisted of five periods:

(i) no push force for 10 minutes,

(ii) 2 N push force for 10 minutes,

(iii) 2 N push force during linearly increasing magnitude of 125 Hz vertical vibration (0 to 88 ms^{-2} r.m.s. over 22 minutes),

(iv) 2 N push force for 10 minutes,

(v) no push force for 10 minutes.

A control condition was similar but without vibration during the third period.

Figure 5-2 shows the sequence of push force and vibration exposure at the right middle finger during the five experimental periods of the vibration condition and the control condition.

The new method of applying the push force first and then the vibration allows the study of the effect of push force and the effect of push force with vibration on finger blood flow. The cessation of vibration before the end of push force allows the study of the effect on finger blood flow of ceasing vibration exposure. The effect of removing push force can be studied.

5.2.4 Measures of finger circulation

Finger blood flow (FBF) was measured in the middle right finger while it was exposed to force and varying vibration. Finger blood flow was also measured in the unexposed right little finger and the unexposed left middle finger. The measurements of finger blood flow were obtained throughout the experiment every 30 seconds. Finger blood flow was measured using an *HVLab* multi-channel plethysmograph according to the technique proposed by Greenfield *et al.* (1963).

5.2.5 Experimental procedure

The experiment was performed in a room with a mean temperature of 30.0 °C (range 29.0 to 31.6 °C). The subjects lay supine on a couch throughout the experiment.

In the vibration condition, the experiment consisted of five periods following acclimatisation: pre-exposure, 2 N push force, 2 N push force and vibration, 2 N push force and recovery (Figure 5-2).

Initially, subjects were acclimatised for 15 minutes. During acclimatisation the subject's hands were supported on a cardboard box alongside the body at about the level of the heart and adjacent to a wooden platform (40 x 12 mm) secured to a vibrator.

During the first of the five periods, the subject's right hand remained in the posture adopted during acclimatisation.

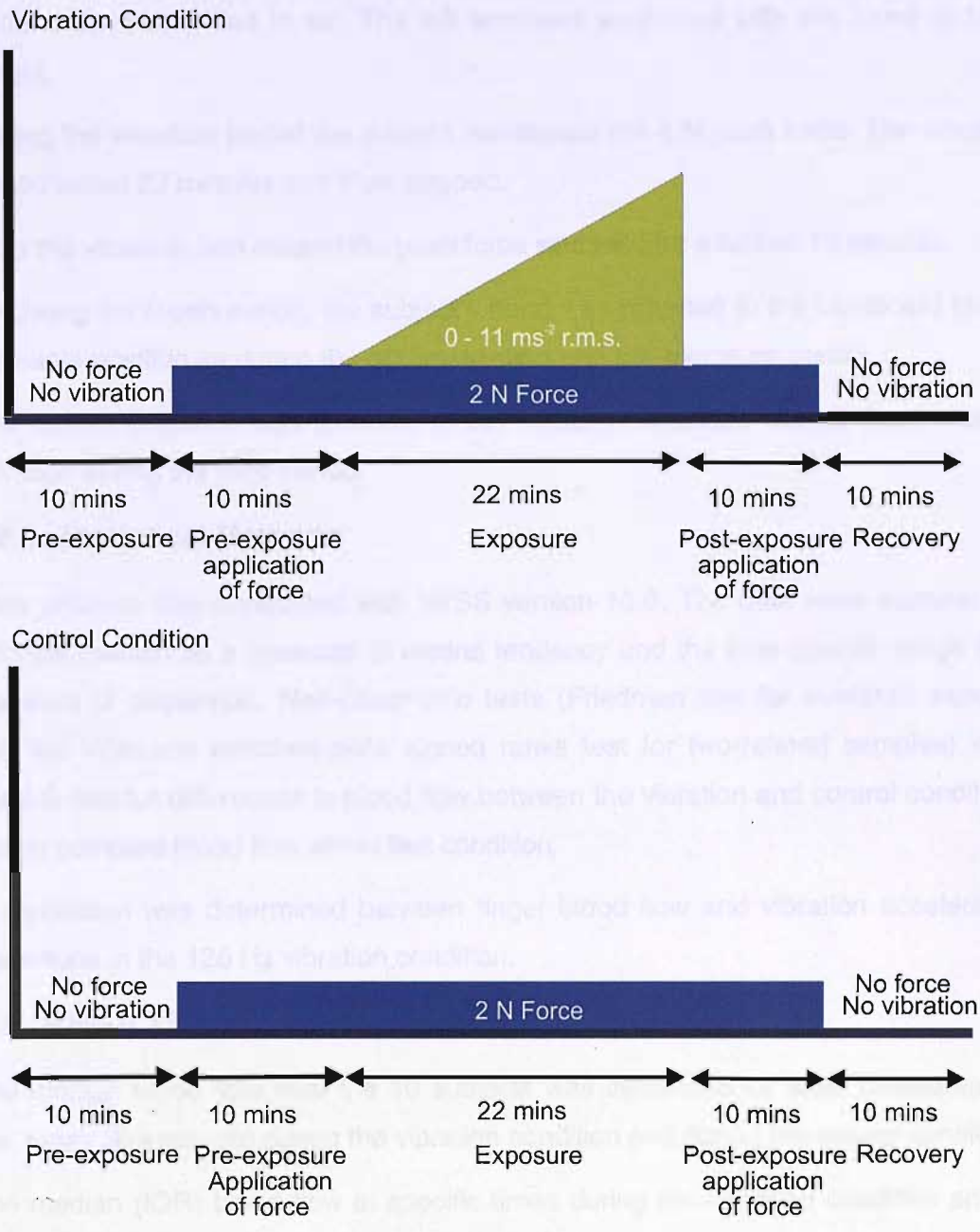


Figure 5-2 The sequence of push force and vibration exposure of the right middle finger during the five experimental periods of the vibration condition and control condition: pre-exposure, pre-exposure application of 2 N force, vibration exposure from 0 to 88 ms^{-2} r.m.s. (0 to 11 ms^{-2} r.m.s. frequency-weighted) at 125 Hz with a push force of 2 N (no vibration in the control condition), post-exposure application of force of 2 N, and recovery.

After the 10-minute pre-exposure measurements in period (i), the subject's right hand was moved so that the middle phalanx of the right middle finger was positioned across the 12 mm of the wooden platform (Figure 5-1). The right wrist and arm were supported independently of the vibrator at heart height. The subject applied a downward push force of 2 N on the wooden platform. The other fingers of the right

hand were suspended in air. The left arm was supported with the hand at heart height.

During the vibration period the subject maintained the 2 N push force. The vibration period lasted 22 minutes and then stopped.

After the vibration had ceased the push force was held for a further 10 minutes.

Following the fourth period, the subject's hand was returned to the cardboard box to the same position as during the acclimatisation and pre-exposure period.

The control condition was identical to the vibration condition except there was no vibration during the third period.

5.2.6 Statistical Methods

Data analysis was conducted with SPSS version 10.0. The data were summarised with the median as a measure of central tendency and the inter-quartile range as a measure of dispersion. Non-parametric tests (Friedman test for *k*-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples) were used to test for differences in blood flow between the vibration and control conditions and to compare blood flow within test condition.

A correlation was determined between finger blood flow and vibration acceleration magnitude in the 125 Hz vibration condition.

5.3 RESULTS

The median blood flow over the 10 subjects was calculated for each measurement (i.e. every 30 seconds) during the vibration condition and during the control condition.

The median (IQR) blood flow at specific times during the vibration condition and at the corresponding time during the control condition may be compared (Table 5-1).

During vibration exposure, finger blood flow measures were extracted by calculating the time at which a specific vibration magnitude would have been reached and then calculating the median finger blood flow of over the 10 subjects obtained for a single measurement at that instant; these values are therefore more variable than the averages obtained over the 20 measures during the 10-minute periods. The vibration magnitudes in Table 5-1 were chosen because they have been used in previous studies and allow comparison with previous results

Table 5-1 Median (interquartile range) finger blood flow (ml/100ml/sec) in 10 subjects during pre-exposure, pre-exposure application of force, vibration exposure 0 to 88 ms^{-2} r.m.s. (0 to 11 ms^{-2} r.m.s. frequency-weighted) at 125 Hz with 2 N push force (no vibration in the control condition), post-exposure application of 2 N force, and recovery.

	Control Condition FBF (ml/100ml/sec)			125 Hz vibration FBF (ml/100ml/sec)		
	Exposed	Unexposed Ipsilateral	Unexposed Contralateral	Exposed	Unexposed Ipsilateral	Unexposed Contralateral
(i) Pre-exposure	1.41 (0.30)	1.08 (0.28)	1.30 (0.25)	1.41 (0.38)	1.26 (0.36)	1.33 (0.31)
(ii) Pre-exposure force	1.06 (0.26)	1.02 (0.15)	1.26 (0.46)	1.01 (0.09)	1.25 (0.39)	1.19 (0.41)
(iii) Vibration and push force:						
6 ms^{-2} r.m.s.	1.10 (0.53)	1.10 (0.45)	1.29 (0.69)	1.06 (0.36)	1.11 (0.41)	1.09 (0.44)
12 ms^{-2} r.m.s.	1.11 (0.30)	1.25 (0.52)	1.34 (0.93)	1.06 (0.34)	1.20 (0.52)	1.37 (0.52)
22 ms^{-2} r.m.s.	0.95 (0.37)	1.11 (0.54)	1.19 (0.62)	0.93 (0.48)	0.87 (0.44)	0.82 (0.34)
44 ms^{-2} r.m.s.	1.10 (0.30)	1.27 (0.41)	1.41 (0.52)	0.65 (0.35)	1.14 (0.38)	1.14 (0.40)
88 ms^{-2} r.m.s.	1.19 (0.56)	1.25 (0.99)	1.38 (0.72)	0.65 (0.30)	1.01 (1.20)	0.85 (0.71)
(iv) Post-exposure force	1.05 (0.47)	1.22 (0.34)	1.22 (0.48)	0.97 (0.24)	1.21 (0.51)	1.06 (0.44)
(v) Recovery	1.39 (0.30)	1.31 (0.36)	1.17 (0.53)	1.37 (0.44)	1.27 (0.30)	1.17 (0.33)

5.3.1 Finger blood flow during pre-exposure period

Over the 20 measurements during the 10-minute pre-exposure period, there were no significant changes in FBF in the exposed finger, the unexposed ipsilateral finger or the unexposed contralateral finger during either the vibration condition or the control condition ($p>0.1$; Friedman).

The percentage changes in finger blood flow relative to pre-exposure finger blood flow are shown in Figure 5-3 and Table 5-2.

Within each of the three fingers, there were no significant differences between the median pre-exposure finger blood flow during the vibration condition and the median finger blood flow during the control condition ($p>0.1$; Wilcoxon).

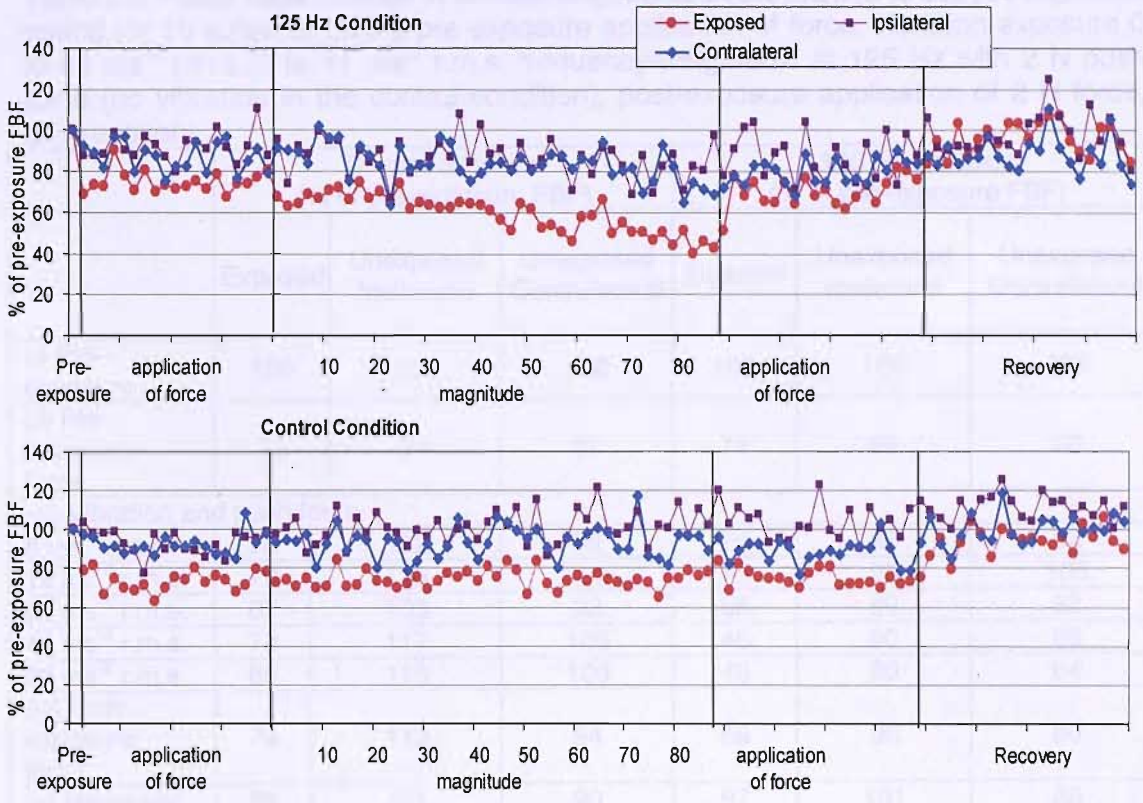


Figure 5-3 Median percentage of pre-exposure finger blood flow in 10 subjects during the five experimental periods in the vibration and control conditions: (i) pre-exposure, (ii) pre-exposure application of 2 N force, (iii) vibration exposure 0 to 88 ms^{-2} r.m.s. (0 to 11 ms^{-2} r.m.s. frequency-weighted) at 125 Hz with a push force of 2 N (no vibration in the control condition), (iv) post-exposure application of 2 N force, and (v) recovery.

5.3.1.1 Finger blood flow during the pre-exposure application of force

Over the 20 measurements during the 10-minute pre-exposure application of force, there were no significant changes in FBF in the exposed finger, the unexposed ipsilateral finger or the unexposed contralateral finger during either the vibration condition or the control condition (p>0.1; Friedman).

In both the vibration condition and the control condition, the 2 N push force reduced the median FBF in the exposed finger compared to the median FBF during the pre-exposure period (p<0.01; Wilcoxon).

In neither the vibration condition nor the control condition, did the 2 N force on the exposed finger change the median FBF in the unexposed ipsilateral finger compared to the median FBF in the unexposed ipsilateral finger during the pre-exposure period (p>0.05).

Table 5-2 Percentage change in median finger blood flow relative to the pre-exposure period for 10 subjects during pre-exposure application of force, vibration exposure 0 to 88 ms^{-2} r.m.s.(0 to 11 ms^{-2} r.m.s. frequency-weighted) at 125 Hz with 2 N push force (no vibration in the control condition), post-exposure application of 2 N force, and recovery.

	Control condition (% of pre-exposure FBF)			125 Hz vibration (% of pre-exposure FBF)		
	Exposed	Unexposed Ipsilateral	Unexposed Contralateral	Exposed	Unexposed Ipsilateral	Unexposed Contralateral
(i) Pre-exposure	100	100	100	100	100	100
(ii) Pre-exposure force	75	94	97	71	99	90
(iii) Vibration and push force:						
6 ms^{-2} r.m.s.	78	102	99	75	88	82
12 ms^{-2} r.m.s.	79	116	103	75	95	103
22 ms^{-2} r.m.s.	67	103	92	66	69	62
44 ms^{-2} r.m.s.	78	117	108	46	90	86
88 ms^{-2} r.m.s.	85	116	106	46	80	64
(iv) Post-exposure force	74	112	94	69	96	80
(v) Recovery	98	121	90	97	101	88

In the vibration condition the 2 N force on the exposed finger reduced FBF in the unexposed contralateral finger compared to FBF during the pre-exposure period (p=0.047). In the control condition the 2 N force on the exposed finger did not change FBF in the unexposed contralateral finger compared to FBF during the pre-exposure period (p>0.05).

5.3.1.2 Finger blood flow during exposure period: control condition (with no vibration)

In the control condition, within each of the three fingers, there were no significant changes in FBF over the 44 measurements obtained during the 22-minute no-vibration exposure period (p>0.1; Friedman).

In the exposed finger there was a significant reduction in median FBF during the exposure period cornpared to the median FBF during the pre-exposure period when there was no force (p<0.05; Wilcoxon). In the unexposed ipsilateral finger and in the unexposed contralateral finger there was no significant difference between the median FBF during the exposure period and the median FBF during the pre-exposure period (p>0.05).

Within each of the three fingers, the continued 22-minute exposure to a push force of 2 N, did not produce any overall change in median finger blood flow compared to the median finger blood flow during the pre-exposure application of force ($p>0.05$; Wilcoxon).

5.3.1.3 Finger blood flow during exposure period: vibration condition

During vibration exposure, in the exposed finger and in the unexposed ipsilateral finger, there were significant changes in FBF within the 44 measurements obtained during the 22-minute exposure ($p<0.05$; Friedman). In the unexposed contralateral finger there was no significant change in FBF during vibration exposure ($p>0.05$).

The instantaneous FBF was tested at each 2.0 ms^{-2} r.m.s. increment in vibration magnitude (i.e. at 2, 4, ... 86, 88 ms^{-2} r.m.s.) during exposure. Compared to the pre-exposure period with no vibration or force, exposure to vibration and force produced a significant reduction in median FBF in the exposed finger at all vibration magnitudes ($p<0.05$; Wilcoxon). Compared to the pre-exposure period, the unexposed ipsilateral finger showed significant reductions in median FBF at 10 of the 44 magnitudes tested (i.e. at 14, 22, 26, 30, 50, 58, 68, 74, 80 and 82 ms^{-2} r.m.s.; $p<0.05$; Wilcoxon). Compared to the pre-exposure period the unexposed contralateral finger showed significant reductions in median FBF at 29 of the 44 magnitudes tested (i.e. at all except 2, 8, 10, 12, 16, 24, 32, 34, 42, 48, 56, 62, 64, 74, 76, ms^{-2} r.m.s; $p<0.05$; Wilcoxon).

In the exposed finger the gradually increasing vibration magnitude produced a significant reduction in overall median FBF over the 22-minute exposure compared to the median FBF during the pre-exposure application of force (i.e. 0.811 compared with 1.006; $p<0.05$; Wilcoxon). There were also significant differences between the median FBF during the pre-exposure application of force and the instantaneous FBF measured at vibration magnitudes between 40 ms^{-2} r.m.s and 88 ms^{-2} r.m.s. ($p<0.05$; Wilcoxon), except at 60 and 64 ms^{-2} r.m.s.

In the unexposed ipsilateral finger, there was a significant reduction in instantaneous FBF compared to the median FBF during the pre-exposure application of force at only five of the 44 magnitudes (i.e. at 2, 14, 22, 58 and 80 ms^{-2} r.m.s.; $p<0.05$; Wilcoxon). In the unexposed contralateral finger, there was a significant reduction in instantaneous FBF compared to the median FBF during the pre-exposure application of force at only four of the 44 magnitudes (i.e. at 8, 22, 52 and 88 ms^{-2} r.m.s.; $p<0.05$; Wilcoxon).

Finger blood flow during the vibration condition at each 2.0 ms^{-2} r.m.s. increment in vibration magnitude (i.e. 2, 4, 6, ... 84, 86, 88 ms^{-2} r.m.s.) was compared with finger blood flow at the corresponding times during the control condition.

In the exposed finger, there were no significant differences in FBF between the vibration condition and the control condition for any vibration magnitude up to 40 ms^{-2} r.m.s. ($p>0.05$; Wilcoxon), except at 2, 18, 34 and 36 ms^{-2} r.m.s. At vibration magnitudes between 42 ms^{-2} r.m.s. and 88 ms^{-2} r.m.s., there were significant reductions in FBF during the vibration condition compared to the control condition ($p<0.05$), except at 54 and 64 ms^{-2} r.m.s.

In the unexposed ipsilateral finger there were no significant differences between the FBF during the vibration condition and FBF at the corresponding times in the control condition. In the unexposed contralateral finger there were significant reductions in FBF in the vibration condition compared to the control condition at 22, 36, 44, 52, 72 and 88 ms^{-2} r.m.s.

5.3.1.4 Finger blood flow post-exposure application of force

Over the 20 measurements during the 10-minute post-exposure application of force, there were no significant changes in FBF in the exposed finger, the unexposed ipsilateral finger or the unexposed contralateral finger, during either the vibration condition or the control condition ($p>0.1$; Friedman).

In both the vibration condition and the control condition, the exposed finger, the unexposed ipsilateral finger and the unexposed contralateral finger, showed no significant difference in median FBF between the post-exposure application of force and the pre-exposure application of force ($p>0.05$; Wilcoxon).

In the control condition the median FBF in the exposed finger, in the unexposed ipsilateral finger and in the unexposed contralateral finger during the post-exposure application of force did not differ from the median blood flow during the preceding 22 minutes of application of force during the exposure period ($p>0.1$; Wilcoxon).

In the vibration condition the median FBF in the exposed finger during the post-vibration period was significantly greater than the median finger blood flow during exposure to vibration at vibration magnitudes of 44 ms^{-2} r.m.s. or more (except at 48, 60 and 64 ms^{-2} r.m.s) ($p<0.05$; Wilcoxon). There were no differences in FBF in either the unexposed ipsilateral finger or the unexposed contralateral finger between the exposure period and the post-exposure application of force period ($p>0.05$; Wilcoxon).

During the post-exposure application of force the FBF did not differ between the vibration condition and the control condition in the exposed finger, the unexposed ipsilateral finger or the unexposed contralateral finger ($p>0.1$; Wilcoxon).

5.3.1.5 Finger blood flow during recovery (i.e. following the removal of push force)

Over the 20 measurements during the 10-minute recovery period, there were no significant changes in FBF in the exposed finger, the unexposed ipsilateral finger or the unexposed contralateral finger, during either the vibration condition or the control condition ($p>0.1$; Friedman).

In the vibration condition for the exposed finger and the unexposed ipsilateral finger, there were no significant differences between the median FBF during the recovery period and the median FBF during the pre-exposure period ($p>0.1$; Wilcoxon). However, the median FBF in the unexposed contralateral finger was significantly less during the recovery period than during the pre-exposure period ($p<0.01$; Wilcoxon).

In the control condition for the exposed finger and the unexposed contralateral finger, there was no significant difference between the median finger blood flow during the recovery period and the median FBF during the pre-exposure period ($p>0.1$; Wilcoxon). However, the median FBF in the unexposed ipsilateral finger was significantly greater during the recovery period than during pre-exposure application of force ($p<0.05$, Wilcoxon).

The removal of the 2-N push force produced a significant increase in blood flow in the exposed finger compared to the median FBF during the post-exposure application of force ($p<0.01$; Wilcoxon). There was no change in FBF in the unexposed ipsilateral finger following the removal of the 2-N push force compared to the post-exposure application of force ($p>0.05$; Wilcoxon).

In the exposed finger, the unexposed ipsilateral finger and the unexposed contralateral finger, there was no difference between the median FBF during recovery in the vibration condition and the median finger blood flow during recovery in the control condition ($p>0.05$; Wilcoxon).

5.4 DISCUSSION

With 125-Hz vibration at magnitudes greater than about 42 ms^{-2} r.m.s. (corresponding to frequency-weighted accelerations greater than about 5 ms^{-2} r.m.s.), there was a significant reduction in finger blood flow in the exposed finger. In this study, there were some significant changes in blood flow in the unexposed

ipsilateral and contralateral fingers. Compared to pre-exposure blood flow, the contralateral finger showed a reduction in finger blood flow at more vibration magnitudes than the ipsilateral finger. Bovenzi *et al.* (1999) found a reduction in blood flow in the unexposed contralateral finger during 15-minute exposures to vibration with a frequency of 125 Hz at vibration magnitudes of 22, 44 and 62 ms^{-2} r.m.s. with a 10-N push force.

The push force reduced finger blood flow in the exposed finger compared to the pre-exposure finger blood flow. In the control condition, the reduction in blood flow in the exposed finger remained constant throughout the 42-minute application of the 2-N push force. The finding of an effect of force in the exposed finger differs from the findings of Bovenzi *et al.* (1998), possibly due to the different contact area and different distribution of force applied with a single finger in this study and multiple fingers in the previous study.

In the control condition, this study did not find a significant effect of force on blood flow in the unexposed ipsilateral finger or the unexposed contralateral finger. There were significant reductions in blood flow in the unexposed contralateral finger associated with simultaneous exposure to vibration and force during the vibration condition. The results suggest that changes in finger blood flow caused by the application of force were mainly restricted to the exposed finger.

In the vibration condition, the finger blood flow in the exposed finger returned to pre-exposure levels after the removal of the push force. Bovenzi *et al.* (1998) found vasodilation following simultaneous cessation of vibration and force in exposed fingers compared to finger blood flow prior to the application of vibration and force. In this study, ending vibration exposure did not produce vasodilation in the exposed finger compared to pre-exposure levels. Similarly, the ending of the 2-N push did not result in vasodilation in the unexposed finger.

The methods used in this study could not be applied to the study of the effects of vibration or force if the instantaneous effects of vibration or force are highly dependent on prior exposure to either vibration or force. In respect of force, the study suggests that the force used here had an instantaneous effect that did not change over 42 minutes and ceased immediately on removal of the force. This suggests that the method might be reasonable for the investigation of the effects of force, including the effects of variable levels of force and the effects of location of force. Previous studies have found that the vasoconstriction during vibration exposure was not highly dependent on the duration of vibration exposure (e.g. Bovenzi *et al.* 1998). However,

the vascular after-effects of vibration are dependent on the duration of prior exposure to vibration (Bovenzi *et al.*, 1995). Possibly, there are two or more mechanisms involved in vasoconstriction caused by hand-transmitted vibration. The current exposures were kept reasonably brief to minimise any cumulative effects while allowing, it was hoped, the monitoring of short-term changes caused by variations in vibration magnitude. The gradual increase in vasoconstriction apparent in the exposed finger as the vibration magnitude increased was probably mainly caused by the increases in vibration magnitude rather than the increased duration of exposure. However, it is not certain that an identical decrease would have been found if the vibration had reduced to zero over a similar subsequent period. Further use of this procedure may therefore require caution to consider the separate vascular changes caused by the instantaneous effects of vibration and the cumulative effects of vibration.

5.5 CONCLUSIONS

A new method for assessing the effects of vibration magnitude on vasoconstriction in the finger found that increases in the magnitude of 125 Hz vibration produced expected decreases in finger blood flow in the exposed finger compared to finger blood flow before exposure and compared to blood flow measured in a control condition with no vibration.

A 2-N push force applied to the finger reduced finger blood flow in the exposed finger compared to blood flow prior to the application of the push force. The reduction in blood flow caused by the force is sufficient to be considered a confounding variable during vibration exposure.

The effect of push force was also sufficient to be of interest to the understanding of vascular changes associated with gripping vibratory tools.

It is tentatively concluded that the method of applying the push force first and then the vibration, followed by the removal of the vibration before the push force, may be applicable to the further study of the effects of both force and vibration on finger blood flow.

CHAPTER 6

COMPARING THE DEPENDENCE OF FINGER BLOOD FLOW ON VIBRATION FREQUENCY AND CONTACT LOCATION

6.1 INTRODUCTION

Chapter 5 reported that during vibration at 125 Hz as the vibration acceleration magnitude increased the finger blood flow reduced. The findings in Chapter 5 give confidence to the findings of Welsh (1980) and Bovenzi *et al.* (1998) who found a stronger vasoconstriction at higher magnitudes of vibration than at lower magnitudes.

Welsh (1980) stated that finger blood flow during vibration exposure was dependent on the frequency of vibration with constant amplitude. However, during vibration exposure with the same frequency-weighted acceleration magnitude, Bovenzi *et al.* 2000 found that the reduction in finger blood flow was similar at frequencies between 31.5 and 250 Hz. The dependence of finger blood flow on vibration frequency and magnitude during vibration exposure is not clear.

Bovenzi *et al.* (2000) found that the vascular response following exposure to equal frequency-weighted accelerations was highly dependent on the vibration frequency. The vascular response following vibration exposure has been reported as highly dependent on the duration of prior exposure to vibration (Bovenzi *et al.*, 1998).

A single simple method of assessing the severity of hand-transmitted vibration cannot predict these two opposing effects reported during and after vibration exposure.

During vibration exposure of the hand or finger there is a static contact force between the vibration surface and the hand or finger. The effect of force to the finger on finger blood flow was investigated in Chapter 5. It was found that the application of a 2-N push force to the medial phalanx reduced blood flow in the exposed finger compared to pre-exposure measures. The force did not cause changes in finger blood flow in other fingers. This is consistent with the findings of Bovenzi *et al.* (2006) who reported that a 2-N push force applied to the finger for 15-minutes reduced finger

blood flow compared to pre-exposure flow. A 5-N push force caused a greater reduction in flow than a 2-N push force.

Users of vibrating tools may expose both the palm and the fingers to force. The application of a 5-N push force to the palm did not change blood flow in the exposed hand (Griffin *et al.*, 2006), but a gradual reduction in flow in the middle finger of the exposed hand was reported over the 15-minute exposure duration. Application of 20 N produced a reduction in blood flow of fingers on the exposed and unexposed hands.

During vibration at 125 Hz at 64 ms^{-2} r.m.s., 20 N push force to the palm was associated with a greater decrease in flow than 5 N push force (Griffin *et al.*, 2006). A 5-N push force to the finger was associated with a greater decrease in flow than 2 N push force, during vibration of 16ms^{-2} r.m.s. at 125 Hz (Bovenzi *et al.*, 2006).

The effect of the location of application of combined push force and vibration at different frequencies and magnitudes on finger blood flow is unknown. This study exposed the palm and the finger to push force and vibration allowing comparison of the reduction in flow between the two locations of application at each frequency and magnitude of vibration.

In Chapter 5 the method of applying the push force first and then the vibration, followed by the removal of the vibration before the push force, seemed suitable to the further study of the effects of both force and vibration on finger blood flow during and after vibration exposure. The linearly increasing (i.e. ramped) magnitude of vibration used in Chapter 5 showed the dependence of finger blood flow on vibration magnitude within the range of magnitudes investigated at 125 Hz. Vibration at various frequencies could show the dependence of finger blood flow on vibration frequency and magnitude.

The aims of this pilot study were to increase understanding of: (i) the influence of vibration magnitude on finger blood flow at different frequencies, and (ii) the contribution of the location of contact to the vasoconstriction occurring during the application of combined force and vibration.

This study was a preliminary conducted on one subject due to the number of conditions required and the originality of the experimental design method.

6.2 METHOD

6.2.1 Subject

One healthy male volunteer aged 26 years participated in the study. He was an office worker with no history of regular exposure to hand-transmitted vibration and no medical disorders known to influence finger blood flow. The subject was a non-smoker and a light drinker. He avoided caffeine for 2 hours prior to testing and avoided alcohol for 12 hours prior to testing.

6.2.2 Equipment

A Derritron VP4 electrodynamic vibrator provided the vibration and was controlled using a computer-based data acquisition system (*HVLab* version 3.81). A Huntleigh force cell was attached to the vibrator table to measure the downward force exerted by the hand. Visual feedback through a force meter allowed subjects to control the application of push force. To monitor vibration, an Entran 233E accelerometer was attached to a metal plate screwed to the top of the force cell.

A cylindrical wooden platform (Figure 6-1) with a domed end was secured on top of the metal plate so that the centre of the subject's palm could be placed on the wooden platform with all fingers suspended in air (Figure 6-2). For the finger contact conditions the same equipment set-up was used.

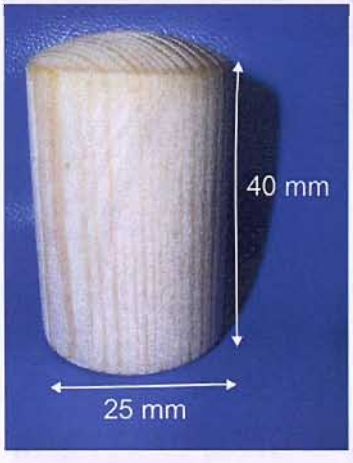


Figure 6-1 Dimensions of the cylindrical wooden platform with domed end.

The subject was supine throughout the experiment with both arms and both hands supported at heart height.

Room temperature was measured using a K-type thermocouple connected to an *HVLab* thermal aesthesiometer that was accurate to 0.5°C. The thermocouple was located close to the head of the subject. Room temperature was controlled to the range 27.0°C to 28.3°C by two radiators.

6.2.3 Experimental Conditions

The subject was exposed on separate days to twelve conditions, consisting of ten vibration sessions and two control sessions with no vibration.

During each session, there were five experimental periods:

(i) Pre-exposure: no push force for 10 minutes,

(ii) Pre-exposure application of force: 2 N push force for 10 minutes,

(iii) Exposure: 2 N push force with vibration magnitude increasing linearly from 0 to 15 ms^{-2} r.m.s. (frequency-weighted) over 30 minutes,

(iv) Post-exposure application of force: 2 N push force for 10 minutes,

(v) Recovery: no push force for 10 minutes.

The control conditions consisted of the same five periods, except the third period consisted of 2 N push force without vibration. There was an acclimatisation period of 15 minutes prior to each session. Each experiment therefore lasted 1 hour and 25 minutes. Figure 6-3 illustrates the five periods of each session.

Sinusoidal vibration was produced in the vertical direction at one of the combinations of vibration frequency and acceleration magnitude shown in Table 6-1.

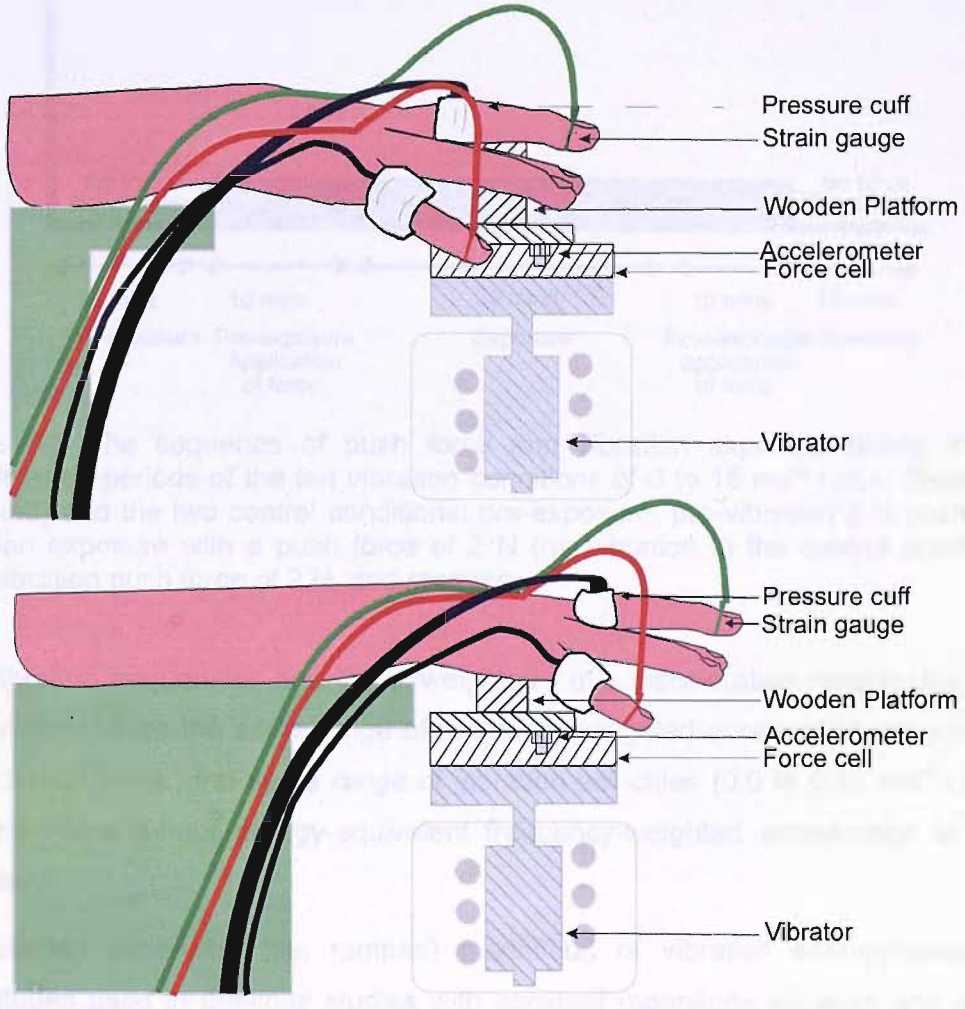


Figure 6-2 Experimental set-up for generating and measuring the vibration, controlling the contact force at the palm and the finger, and measuring finger blood flow.

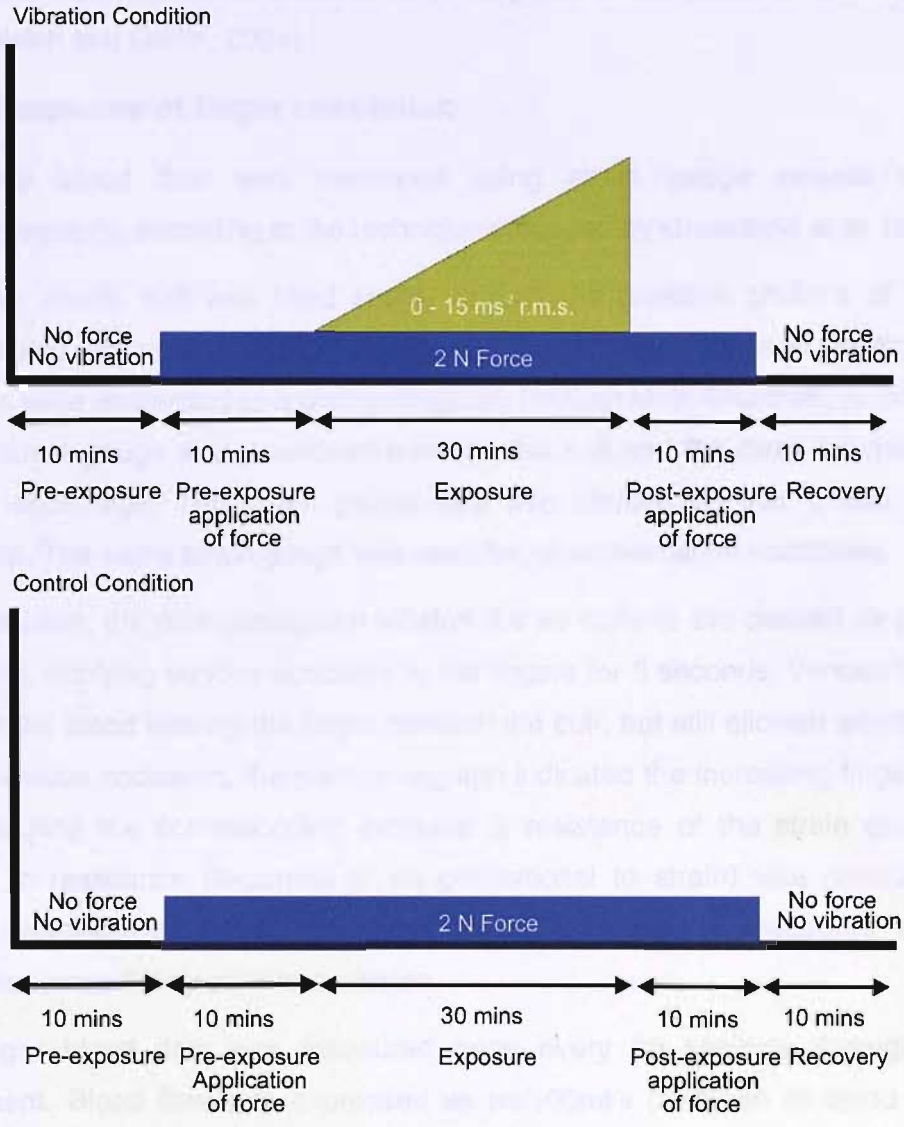


Figure 6-3 The sequence of push force and vibration exposure during the five experimental periods of the ten vibration conditions of 0 to 15 ms^{-2} r.m.s. (frequency-weighted) and the two control conditions: pre-exposure, pre-vibration 2 N push force, vibration exposure with a push force of 2 N (no vibration in the control conditions), post-vibration push force of 2 N, and recovery.

The vibration frequencies and the unweighted r.m.s. acceleration magnitudes were chosen to produce the same range of frequency-weighted acceleration magnitudes, 0 to 15 ms^{-2} r.m.s., the same range of vibration velocities (0.0 to 0.15 ms^{-1} r.m.s.), and the same 8-hour energy-equivalent frequency-weighted acceleration in each condition.

The linearly increasing (i.e. ramped) magnitude of vibration encompassed the magnitudes used in previous studies with constant magnitude vibration and allows comparisons at specific magnitudes.

A 2 N push force was used so as to be consistent with previous studies (Welsh, 2003; Welsh and Griffin, 2004).

6.2.4 Measures of finger circulation

Peripheral blood flow was measured using strain gauge venous occlusion plethysmography according to the technique proposed by Greenfield *et al.* (1963).

A flexible plastic cuff was fitted snugly around the proximal phalanx of the right middle finger, the right little finger and the left middle finger. The soft plastic tubes of the cuffs were connected to a plethysmograph (*HVLab* Multi-Channel). A mercury-in-silastic strain gauge was positioned between the nail and the distal interphalangeal joint of each digit. The strain gauge size was chosen so that it was in slight extension. The same strain gauge was used for all experimental conditions.

On instruction, the plethysmograph inflated the air cuffs to the desired air pressure, 60 mmHg, applying venous occlusion to the fingers for 5 seconds. Venous occlusion stopped the blood leaving the finger beneath the cuff, but still allowed arterial inflow. During venous occlusion, the plethysmograph indicated the increasing finger volume by measuring the corresponding increase in resistance of the strain gauge. The change in resistance (assumed to be proportional to strain) was recorded as a relative percentage change from the baseline resistance measured during a calibration immediately prior to occlusion.

The finger blood flow was measured once every 60 seconds throughout the experiment. Blood flow was expressed as ml/100ml/s (millilitres of blood per 100 millilitres of tissue per second). Finger skin temperature was measured by a thermocouple attached by micro pore tape to the distal phalanx of the right middle finger.

Table 6-1 Vibration frequencies and vibration magnitudes investigated.

Vibration frequency (Hz)	Unweighted acceleration (ms^{-2} r.m.s)	Frequency-weighted acceleration (ms^{-2} r.m.s)	$A(8)$ (ms^{-2} r.m.s)
No vibration	0	0	0
16	0 – 15.0	0 – 15	2.18
31.5	0 – 29.5	0 – 15	2.18
63	0 – 59.1	0 – 15	2.18
125	0 – 117.2	0 – 15	2.18
250	0 – 234.3	0 – 15	2.18

6.2.5 Experimental Procedure

Initially, the subject was acclimatised for 15 minutes with his hands supported alongside the body at about the level of the heart.

Pre-exposure blood flow measurements were taken over 10 minutes while the subject remained in the same posture adopted during acclimatisation. The right hand of the subject was supported by a wooden box at the same height as the hand when located on the wooden platform.

To apply a push force, the experimenter positioned the subject's right hand with either the centre of the palm or the medial phalanx of the middle right finger in contact with the wooden platform secured to the vibrator. In the six conditions with the palm in contact with the wooden platform, the hand was kept in a comfortable posture with the fingers suspended without contact. In the 6 conditions with the finger in contact with the wooden platform, the hand was kept in a comfortable posture with the right thumb, index, ring and little fingers suspended without contact. The subject applied a downward force of 2 N, with the right palm or middle finger, continuously for 50 minutes.

In the vibration condition, the vibration started at 0.0 ms^{-2} r.m.s. and increased linearly to 15 ms^{-2} r.m.s. (frequency-weighted) over 30 minutes and then stopped. The push force was maintained at 2 N for the duration of the vibration.

After the vibration had ceased, the push force was held for a further 10 minutes. At the 60^{th} minute, the subject was asked to release the push force whilst keeping the hand in the same posture. The experimenter then repositioned the subject's hand so that it was again supported alongside the body at heart level as during the pre-exposure period.

The control condition was identical to the vibration condition except there was no vibration during the third period.

6.3 RESULTS

The results show the finger blood flow measured in one subject and therefore do not allow definitive conclusions on the effects of any variables. However, some tentative observations are possible.

Individual measurements of the finger blood flow in a single subject always show much variability. The medians of ten successive measures on each finger have been used to illustrate the systematic changes in finger blood flow on that finger. The medians of ten successive measures produced one measure during each of the 10-

minute periods; pre-exposure application of force, post-exposure application of force, recovery (except the pre-exposure period) and six measures during the 30-minute exposure period.

The reported values are the medians of five measurements over 5 minutes corresponding to 0.0 – 2.5 ms^{-2} r.m.s., 2.5 – 5.0 ms^{-2} r.m.s., 5.0 – 7.5 ms^{-2} r.m.s., 7.5 – 10.0 ms^{-2} r.m.s., 10.0 – 12.5 ms^{-2} r.m.s. and 12.5 – 15.0 ms^{-2} r.m.s. (frequency-weighted).

The finger blood flow was expressed as a percentage of the pre-exposure finger blood flow (i.e. %FBF). For each subject, the %FBP was calculated at each vibration magnitude during exposure to each frequency.

Figure 6-4 shows the percentage reduction in finger blood flow in the exposed right middle finger and the unexposed right little finger and left middle finger, during the five periods of the vibration and during the control condition with vibration applied at the finger and at the palm.

6.3.1 Finger blood flow during 'pre-exposure'

In the pre-exposure period there appears to be no difference in FBF in the right middle finger between the 10 vibration conditions and the two control conditions with either palm contact or finger contact. There also appears to be no difference in FBF in the right little and left middle fingers between the 10 vibration conditions and the two control conditions with either palm contact or finger contact.

6.3.2 Finger blood flow during 'pre-exposure application of force'

In the five vibration conditions and the control condition, the pre-exposure application of force by the finger appears to have reduced median blood flow compared to finger blood flow during the pre-exposure period.

In the five vibration conditions, the pre-exposure application of force by the palm appears to have produced little or no change in FBF in the right middle finger compared to FBF during the pre-exposure period. However, some reduction in FBF is apparent in the control condition.

The pre-exposure application of force by the finger and the palm appears to have produced some small change in FBF in the unexposed right little and left middle fingers.

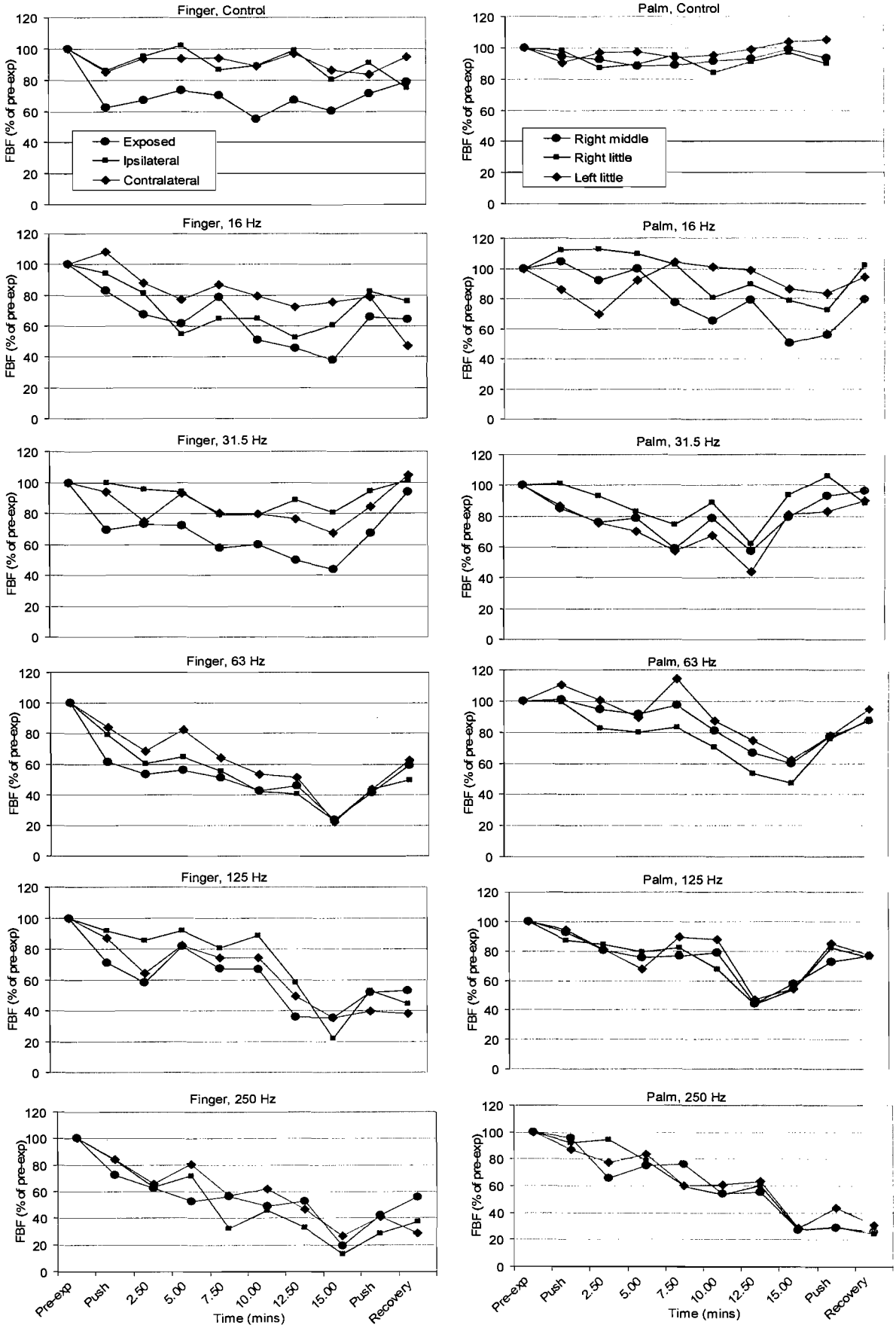


Figure 6-4 Percentage median finger blood flow in the right middle finger in one subject in the control condition and five vibration conditions of 0 to 15 ms^{-2} r.m.s. (frequency-weighted), during the five periods of each condition with both finger and palm contact with the applicator.

6.3.3 Finger blood flow during 'exposure'

During the exposure period, in the two control conditions where there was palm contact and finger contact with the applicator, the 30-minute exposure to a push force of 2 N without vibration produced no obvious consistent change in finger blood flow compared to the blood flow during the 'pre-exposure application of force' period.

In all vibration conditions, and with both contact conditions, there was a tendency for blood flow in all fingers to reduce as the vibration magnitude increased during the 30-minute exposure to vibration with a push force of 2 N. The reduction seems to have been greater with the higher frequencies, even though the frequency-weighted vibration magnitude was the same with all frequencies.

In all vibration conditions, the reduction in blood flow in all fingers, during vibration exposure appears to have been stronger with the finger in contact with the applicator than with the palm in contact with the applicator.

In all vibration conditions, with finger contact the reduction in blood flow was more pronounced in the exposed right middle finger than in the unexposed right little and left middle fingers. With palm contact the reduction in blood flow was similar in the exposed and unexposed fingers.

6.3.4 Finger blood flow during the 'post-exposure application of force'

With both contact conditions, in the control condition, the finger blood flow during the post-exposure application of force seems to have been similar to the blood flow during the pre-exposure application of force.

With both contact conditions, after exposure to 16 Hz vibration there was little change in finger blood flow in any finger immediately after cessation of vibration. After stopping vibration at 31.5, 63 and 125 Hz, with both contact conditions, there was an immediate increase in blood flow. The increase in blood flow in all fingers, immediately after cessation of vibration appears to have been stronger with palm contact than with finger contact.

There was little or no change in finger blood flow immediately after stopping the 250 Hz vibration. With both contact conditions, the finger blood flow remained much reduced compared to the blood flow during the pre-exposure application of force.

6.3.5 Finger blood flow during the 'recovery period' (i.e. following the removal of push force)

In the recovery period, there was a tendency for the blood flow in all three fingers to be similar after both finger contact and palm contact.

In the control conditions, with palm contact, the finger blood flow during the recovery seems to have been similar to the blood flow during the post-exposure application of force period. With finger contact, the finger blood flow increased during the recovery compared to during the post-exposure application of force period.

During the recovery period, after palm contact, there was a tendency for the blood flow to return to pre-exposure levels following exposure to 16 Hz, 31.5 Hz, and 63 Hz vibration. After finger contact, there was a tendency to return to pre-exposure finger blood flow following exposure to 31.5 Hz vibration.

In the palm contact condition, the recovery period following exposure to 125 Hz shows only a slightly reduced finger blood flow compared to that during the pre-exposure period. After finger contact with 125 Hz vibration, the blood flow remained greatly reduced compared to that during the pre-exposure period.

In both palm contact conditions, the recovery period following exposure to 250 Hz vibration shows a considerably reduced finger blood flow relative to that during the pre-exposure period and during the post-application of force period.

6.4 DISCUSSION

The results of the pilot study do not allow definitive conclusions on the effects of any variables. However, some tentative observations are possible.

The reduction in blood flow caused by a 2-N push force may be expected to depend on both the contact location and the contact area of the force applied to the hand. In this study, the contact area and the wooden contact applicator were the same in both contact conditions. The push force of 2 N applied to the palm of the right hand did not appear to reduce finger blood flow in the exposed right middle finger, whereas the same push force applied to the medial phalanx of the middle finger did appear to reduce blood flow in that finger. Previous studies have found that the application of a 2 N push force to the medial phalanx of a finger reduces finger blood flow (*Bovenzi et al.*, 2006a). With force applied at the palm, compression of the vascular system so as to reduce the circulation to the finger is less likely. With both contact conditions, the unexposed fingers showed a little change in blood flow with the application of force to the right finger or palm.

In this study, finger blood flow in all fingers, reduced progressively with increases in vibration magnitude. The findings of this study are, to some extent, consistent with the findings of Bovenzi *et al.* (1999) who reported that with greater vibration magnitudes there was a greater reduction in blood flow in the fingers exposed to vibration.

In this study, each vibration frequency had the same range of frequency-weighted accelerations. However, the reduction in finger blood flow during vibration exposure compared to pre-exposure blood flow varied with vibration frequency as well as vibration magnitude. At all vibration frequencies, as the vibration magnitude increased the reduction in blood flow became stronger. Bovenzi *et al.* (2000) found no significant difference in the reduction in finger blood flow between 31.5 and 250 Hz when using the same frequency-weighted acceleration magnitude at each frequency. The main differences between this study and the study reported by Bovenzi *et al.* (2000) are: (i) the magnitudes in this study were three times greater than those used previously, (ii) the duration of vibration exposure was longer in this study, (iii) the vibration and force were applied to a smaller contact area in this study, and (iv) a greater pressure was applied in this study.

The reduction in finger blood flow during exposure to vibration seemed to have been affected by the contact location of the push force. In this study, a greater reduction in blood flow at all frequencies and magnitudes was seen in the exposed finger when the push force was applied by the finger than when the push force was applied by the palm. The reduction in finger blood flow during exposure to the finger was greater in the exposed finger than in the unexposed digits. The greater reduction in blood flow with force and vibration applied to the finger may arise from the accumulated effects of compression of the vascular system and vibration-induced vasoconstriction. Future methods of evaluating the severity of vibration from tools could consider the reporting of push force and the location of push force to the hand.

After the cessation of vibration, the post-vibration application of force produced different finger blood flow responses dependent on frequency, consistent with Bovenzi *et al.* (2000). At all frequencies except at 250 Hz, finger contact with the applicator resulted in lower finger blood flow after the cessation of vibration than with palm contact. The low blood flow after finger contact condition may have been a result of continuous 2 N push force compression of the vascular system in the finger. Bovenzi *et al.* (1998) found vasodilation when push force and vibration ceased simultaneously. In this study the cessation of vibration with continuing push force did not produce vasodilation in any vibration condition.

After the cessation of push force during the recovery period, finger blood flow seemed dependent on vibration frequency, as reported by Bovenzi *et al.* (2000). An effect of contact location on blood flow is evident with each frequency of vibration, with the finger contact condition producing lower blood flow than the palm condition, except at 250 Hz. After exposure to 250 Hz, both contact locations show a continued large reduction in blood flow. It therefore seems that the mechanisms controlling blood flow after vibration exposure have a frequency dependency different from that in current standards.

6.5 CONCLUSION

A 2-N push force applied to the finger appears to have affected finger blood flow differently from the same force applied to the palm. A greater reduction in finger blood flow was seen with the finger in contact with a vibrating platform than with the palm in contact with a vibrating platform. A greater reduction in finger blood flow was seen in the exposed finger than in the unexposed fingers with the finger in contact with the wooden platform. With vibration applied to the finger, a stronger reduction in blood flow was seen at each vibration frequency and magnitude during and after vibration exposure, than with vibration applied to the palm.

The higher the frequency of vibration and the greater the magnitude of vibration, the stronger is the reduction in finger blood flow during and after vibration exposure.

CHAPTER 7

THE DEPENDENCE OF FINGER BLOOD FLOW ON VIBRATION FREQUENCY AND MAGNITUDE APPLIED TO THE PALM

7.1 INTRODUCTION

Previous experimental studies have suggested that the vascular response during vibration depends primarily on the magnitude of vibration, whereas finger blood flow (FBF) after exposure is more influenced by the duration of the prior exposure to vibration (Bovenzi *et al.*, 2001). However, Chapters 5 and 6 suggest that the vascular responses during and after vibration are influenced by the vibration magnitude and frequency.

In Chapter 5, finger blood flow in all fingers reduced progressively with increases in the magnitude of 125-Hz vibration from 0 to 11 ms^{-2} r.m.s. The findings of Chapter 5 are, to some extent, consistent with the findings of Bovenzi *et al.* (1999) who reported that with greater vibration magnitudes there was a greater reduction in blood flow (over the range 22 to 62 ms^{-2} r.m.s.). Chapter 6 identified that at vibration frequencies from 16 to 250 Hz, as the vibration magnitude increased the reduction in blood flow became stronger.

Chapter 6 investigated the FBF on vibration frequency during vibration. A greater reduction in blood flow in both hands was found at higher frequencies than at lower frequencies in the range of 16 to 250 Hz with magnitudes from 0 to 15 ms^{-2} r.m.s. Bovenzi *et al.* (2000) reported a greater reduction in flow in the unexposed hand, at higher frequencies than at lower frequencies with vibration at the same frequency-weighted acceleration at all frequencies (5.5 ms^{-2} r.m.s). However, in the exposed hand Bovenzi *et al.* (2000) found that, compared to FBF prior to exposure, the FBF during vibration was strongly reduced over the range 31.5 to 250 Hz, and only slightly reduced with 16 Hz vibration. Similarly, Furuta *et al.* (1991) found more pronounced vasoconstriction at frequencies greater than 30 Hz than at lower frequencies, with acceleration magnitudes of 10 and 50 ms^{-2} r.m.s. The dependence of finger blood flow in both hands on vibration frequency during vibration is not clearly established.

After the end of vibration, Chapter 6 found that higher frequencies produced a greater vasoconstriction than lower frequencies (in the range of 16 to 250 Hz with magnitudes from 0 to 15 ms^{-2} r.m.s.). After an initial vasodilation in the exposed digit, Bovenzi *et al.*

(2000) found that finger blood flow was inversely related to the vibration frequency over the range 16 to 250 Hz after exposure to a frequency-weighted acceleration of 5.5 ms^{-2} r.m.s. As in Chapter 6, Bovenzi *et al.* (2000) found that the greater the frequency of vibration the stronger the reduction in FBF in both the exposed and non-exposed hands after vibration had ceased. The Bovenzi *et al.* (2000) results are consistent with the findings in Chapter 6 that there is a greater vasoconstriction after exposure to higher vibration frequencies than after explore to lower frequencies (in the range of 16 to 250 Hz with magnitudes from 0 to 15 ms^{-2} r.m.s.). In contrast, Nohara *et al.* (1986) found a stronger vasoconstriction following vibration of 50 ms^{-2} r.m.s. at 60 and 480 Hz than following vibration at 30, 120, 240 and 960 Hz.

In Chapter 6 it was found that the reduction in finger blood flow during exposure to vibration was affected by the contact location of the push force. It is possible that in previous experimental studies the dependence of finger blood flow in the exposed digit, during, and may be after, vibration was confounded by the effect of push force. Chapter 6 was a pilot study with one subject. The aim of the pilot study was to identify the effect of contact location on finger blood flow in order that the confounding affect of push force could be eliminated in the design of the present study. The study reported here was designed to investigate the dependence of finger blood flow on the frequency and magnitude of vibration transmitted to the hand. It was performed with similar ranges of vibration velocity at all frequencies – and hence similar ranges of frequency-weighted vibration magnitudes according to current standards. It was hypothesised that during exposure of one hand to vibration, finger blood flow in both the exposed and the non-exposed hand would decrease as the vibration magnitude increased. It was further hypothesised that the degree of vasoconstriction in the exposed and non-exposed hand during and after exposure to vibration would be dependent on vibration frequency.

7.2 METHOD

7.2.1 Subjects

Twelve healthy male volunteers aged 26 to 32 years participated in the study. Subjects were office workers with no history of regular exposure to hand-transmitted vibration and no medical disorders known to influence finger blood flow. The subjects avoided caffeine for 2 hours prior to testing and avoided alcohol for 12 hours prior to testing.

7.2.2 Measurement of finger blood flow

Peripheral blood flow was measured using strain gauge venous occlusion plethysmography according to the technique proposed by Greenfield *et al.* (1963).

A flexible plastic cuff was fitted snugly around the proximal phalanx of the right middle finger, right little finger and left middle finger. The soft plastic tubes of the cuffs were connected to a plethysmograph (*HVLab* multi-channel). A mercury-in-silastic strain gauge was positioned between the nail and the distal interphalangeal joint of each digit. The strain gauge size was chosen so that it was in slight extension. The same strain gauge was used on each subject for all experimental conditions.

On instruction, the plethysmograph inflated the air cuffs to the desired air pressure, 60 mmHg, applying venous occlusion to the fingers for 5 seconds. The venous occlusion stopped the blood leaving the finger beneath the cuff, but allowed arterial inflow. During venous occlusion, the plethysmograph indicated the increasing finger volume by measuring the corresponding increase in resistance of the strain gauge. The change in resistance (which was proportional to strain) was recorded as a relative percentage change from the baseline resistance measured during a calibration immediately prior to occlusion.

The finger blood flow was measured once every 60 seconds throughout the experiment. Blood flow was expressed as ml/100ml/s (millilitres of blood per 100 millilitres of tissue per second). Finger skin temperature was measured by a thermocouple attached by micro pore tape to the distal phalanx of the right middle finger.

7.2.3 Equipment

A Derritron VP4 electrodynamic vibrator provided the vibration and was controlled using a computer-based data acquisition system (*HVLab* version 3.81). A Huntleigh force cell was attached to the vibrator table to measure the downward force exerted by the hand. Visual feedback through a force meter allowed subjects to control the application of push force. To monitor vibration, an Entran 233E accelerometer was attached to a metal plate screwed to the top of the force cell.

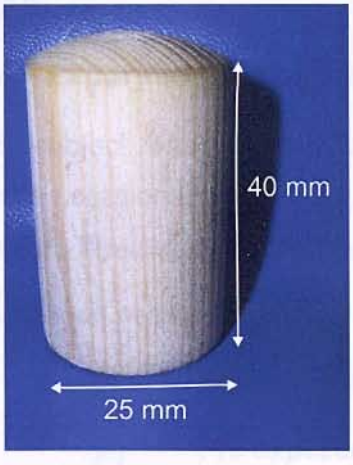


Figure 7-1 Dimensions of the cylindrical wooden platform with domed end.

A cylindrical wooden platform (Figure 7-1) with a domed end was secured on top of the metal plate so that the centre of the subject's palm could be placed on the wooden platform with all fingers suspended in air (Figure 7-2).

The diameter of the circular contact was 25 mm, the

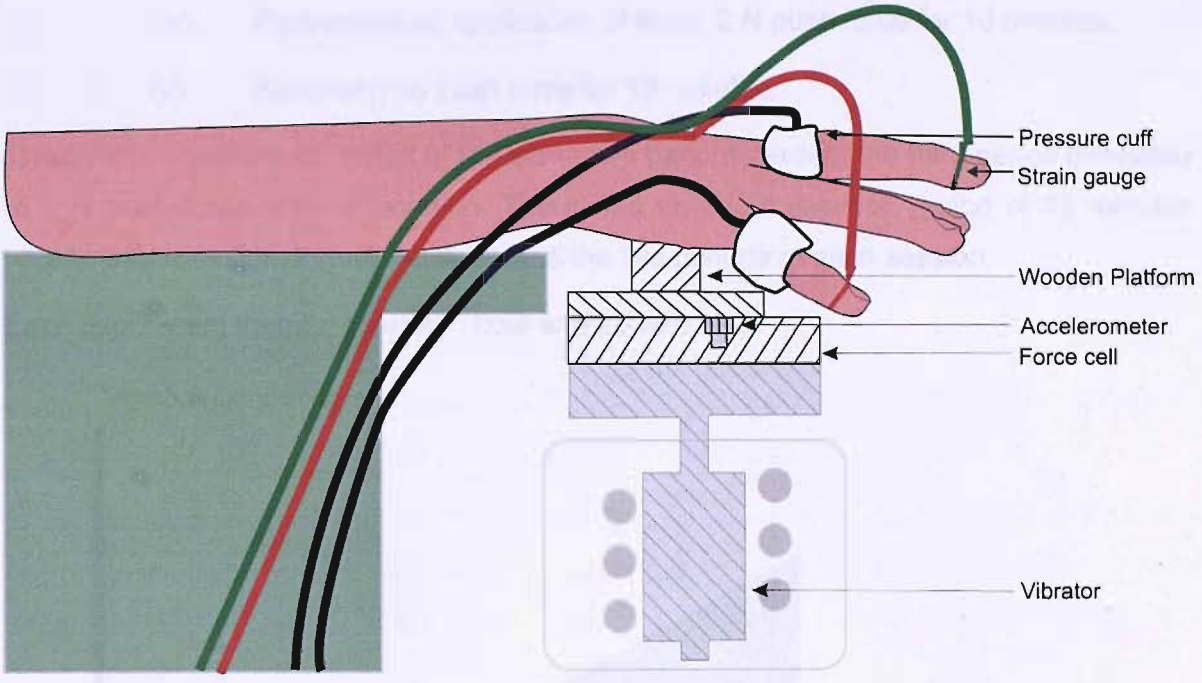


Figure 7-2 Experimental arrangement for generating and measuring the vibration, controlling the contact force at the palm and measuring finger blood flow.

radius of curvature of the dome being 25 mm.

The subjects were supine throughout the experiment with both arms and both hands supported at heart height.

Room temperature was measured using a K-type thermocouple connected to an *HVLab* thermal aesthesiometer that was accurate to 0.5°C. Room temperature was controlled to the range 26.0°C to 27.5°C. The thermocouple was located close to the head of the subject.

7.2.4 Experimental conditions

Each subject was exposed on separate days to seven conditions, consisting of six vibration sessions (with 16, 31.5, 63, 125, 250, or 315 Hz) and one control session with no vibration. The order of conditions was randomised.

During each session of the experiment, there were five experimental periods:

(i) Pre-exposure: no push force for 10 minutes,

(ii) Pre-exposure application of force: 2 N push force for 10 minutes,

(iii) Exposure: 2 N push force with vibration magnitude increasing linearly from 0 to 15 ms^{-2} r.m.s. (frequency-weighted) over 30 minutes (0 to 11 ms^{-2} r.m.s. at 315 Hz),

(iv) Post-exposure application of force: 2 N push force for 10 minutes,

(v) Recovery: no push force for 10 minutes.

The control condition consisted of the same five periods, except the third period consisted of 2 N push force without vibration. There was an acclimatisation period of 15 minutes prior to each session. Figure 7-3 illustrates the five periods of each session.

Each experiment therefore lasted 1 hour and 25 minutes.

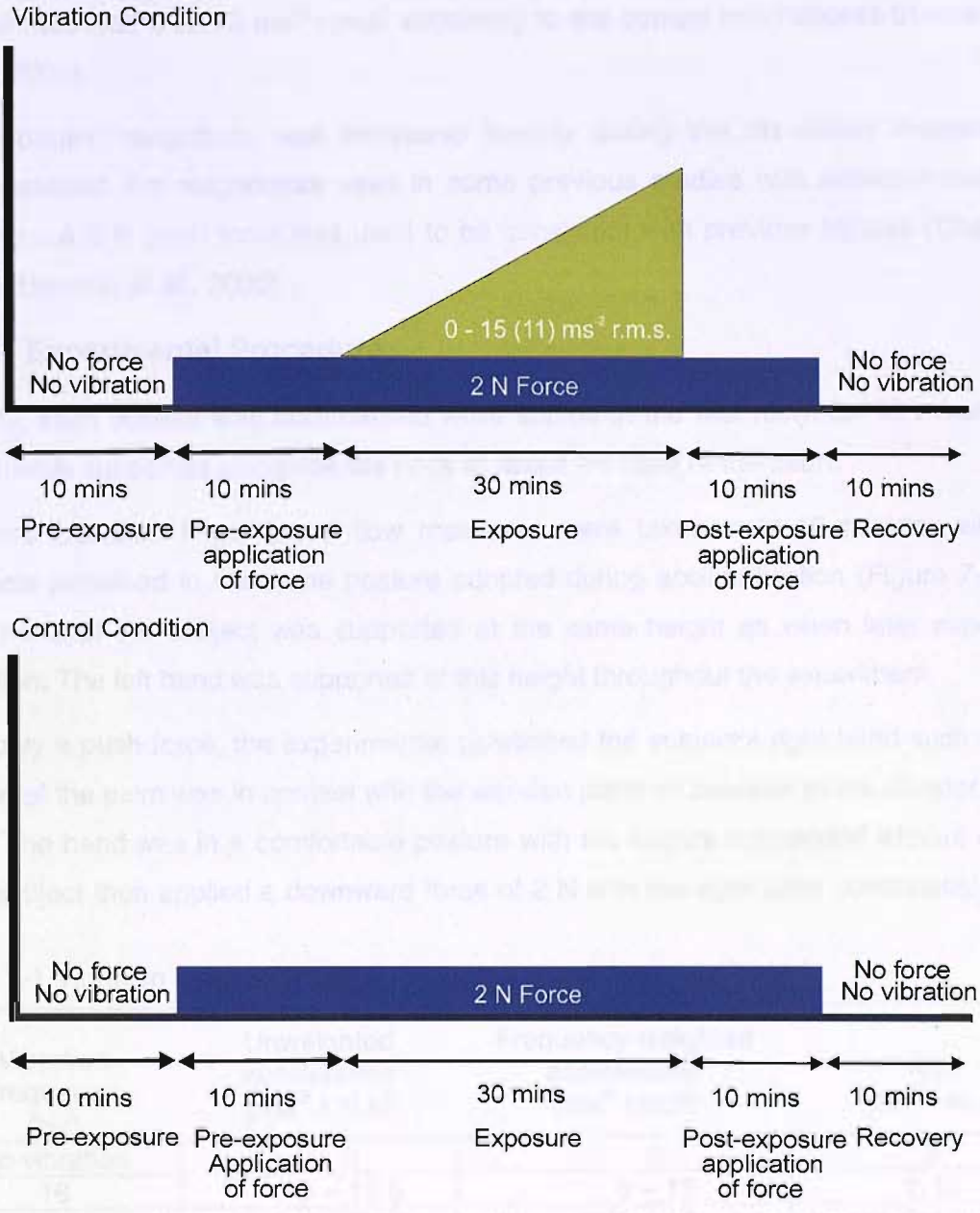


Figure 7-3 The sequence of push force and vibration exposure during the five experimental periods of the six vibration conditions of 0 to 15 ms^{-2} r.m.s. (frequency-weighted) and 0 to 11 ms^{-2} r.m.s. (frequency-weighted) at 315 Hz and the control condition: pre-exposure, pre-exposure application of 2 N push force, vibration exposure with a push force of 2 N (no vibration in the control conditions), post-exposure application of 2 N push force, and recovery

Sinusoidal vibration was produced in the vertical direction at one of the combinations of vibration frequencies and acceleration magnitudes shown in Table 7-1.

The vibration frequencies and the unweighted r.m.s. acceleration magnitudes were chosen to produce the same range of vibration velocities (0.0 to 0.15 ms^{-1} r.m.s.), except at 315 Hz where the range was 0 to 0.11 ms^{-1} r.m.s. because of the limitations of the vibrator and the acoustic noise generated at high magnitudes. The use of the same range of velocities at each frequency (except 315 Hz) means that the range of frequency-weighted acceleration magnitudes was 0 to 15 ms^{-2} r.m.s. according to the current International Standard (ISO 5349, 2001).

The vibration magnitude was increased linearly during the 30-minute exposure and encompassed the magnitudes used in some previous studies with constant magnitude vibration. A 2-N push force was used to be consistent with previous studies (Chapters 5 and 6; Bovenzi *et al.*, 2006).

7.2.5 Experimental Procedure

Initially, each subject was acclimatised while supine in the test room for 15 minutes with their hands supported alongside the body at about the level of the heart.

The pre-exposure finger blood flow measures were taken over 10 minutes while the subjects remained in the same posture adopted during acclimatisation (Figure 7-3). The right hand of the subject was supported at the same height as when later exposed to vibration. The left hand was supported at this height throughout the experiment.

To apply a push force, the experimenter positioned the subject's right hand such that the centre of the palm was in contact with the wooden platform secured to the vibrator (Figure 9-1). The hand was in a comfortable posture with the fingers suspended without contact. The subject then applied a downward force of 2 N with the right palm continuously for 50

Table 7-1 Vibration frequencies and vibration magnitudes investigated.

Vibration frequency (Hz)	Unweighted acceleration (ms^{-2} r.m.s)	Frequency-weighted acceleration (ms^{-2} r.m.s)	*A*(8) (ms^{-2} r.m.s)
No vibration	0	0	0
16	0 – 15.0	0 – 15	2.18
31.5	0 – 29.5	0 – 15	2.18
63	0 – 59.1	0 – 15	2.18
125	0 – 117.2	0 – 15	2.18
250	0 – 234.3	0 – 15	2.18
315	0 – 220.0	0 - 11	1.60

minutes (i.e., throughout periods (ii), (iii), and (iv)). For the vibration at frequencies between 16 and 250 Hz, the vibration started at 0.0 ms^{-2} r.m.s. and increased linearly to 15.0 ms^{-2} r.m.s. (frequency-weighted) over 30 minutes and then stopped. With 315 Hz, the vibration started at 0.0 ms^{-2} r.m.s. and increased linearly to 11.0 ms^{-2} r.m.s. (frequency-weighted) over 30 minutes and then stopped.

After the vibration ceased, the push force was held for a further 10 minutes (i.e., period (iv)). At the 60^{th} minute, the subject was asked to release the push force whilst keeping the hand in the same posture. The experimenter then repositioned the subject's hand so that it was again supported alongside the body at heart level as during the pre-exposure period.

The control condition was identical to the vibration conditions except there was no vibration during the third period.

The study was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).

7.2.6 Statistical Methods

Data analysis was performed with the software package SPSS (version 14.0). The data were summarised with the median as a measure of central tendency and the inter-quartile range (IQR) as a measure of dispersion. Non-parametric tests (Friedman test for *k*-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed in the statistical analysis.

The Friedman test was used to test for differences between the 10 sets of finger blood flow measurements during the 10-minute pre-exposure period, the 10-minute pre-exposure application of force, the 30-minute exposure to force and vibration, the 10-minute post-exposure application of force, and the 10-minute recovery period. A Wilcoxon matched-pairs signed ranks test was then used to investigate differences between the median finger blood flow during the pre-exposure period, the pre-exposure application of force, the post-exposure period, and the recovery period.

To express the functional relationship between vibration magnitude and finger blood flow, least squares linear regressions were fitted to the raw FBF of each subject as a function of the vibration magnitude at each frequency. For the control condition, the least squares regression lines were fitted between the FBF of each subject and the time interval during the 'no vibration exposure period'.

The median values of the regression slopes were calculated to represent the rate of change in FBF with increasing vibration magnitude at each frequency. A Friedman test

compared the slopes to test for differences over the six frequencies. Differences in slope between each vibration frequency and the control condition with no vibration were investigated using Wilcoxon matched-pairs signed ranks tests.

The finger blood flow was expressed as a percentage of the pre-exposure finger blood flow (i.e. %FBF). For each subject, the %FBP was calculated at each vibration magnitude during exposure to each frequency and a best-fit line was calculated by linear regression for each frequency to show the change in %FBF with increasing acceleration.

The criterion for statistical significance was $p<0.05$.

7.3 RESULTS

Air temperature in the laboratory did not differ across the seven experimental conditions (range of median values 26.2 to 27.0; $p>0.1$; Friedman). Finger skin temperature did not differ across the seven experimental conditions during the pre-exposure period ($p=0.773$; Friedman), the pre-exposure application of force ($p=0.113$), vibration exposure ($p=0.167$), post-vibration application of force ($p=0.287$) or the recovery period ($p=0.373$).

Table 7-2 reports the median values for FBF in the exposed right middle finger throughout the experimental sessions.

Figure 7-4 shows the median %FBF in the exposed middle and little right fingers and non-exposed left middle finger, over the two pre-exposure periods and the two post exposure periods of the experiment for the control condition (with no vibration) and for the six sessions with vibration at 16, 31.5, 63, 125, 250 and 315 Hz

Table 7-2 Median values of FBF measured in the exposed middle right finger over the five periods (pre-exposure, pre-exposure application of force, exposure 0 to 15 ms^{-2} r.m.s. (frequency-weighted) and 0 to 11 ms^{-2} r.m.s. (frequency-weighted) at 315 Hz, post-exposure application of force, recovery) for the control condition and for the experimental sessions with exposure to vibration at 16, 31.5, 63, 125, 250 and 315 Hz during the exposure period. Accelerations for 315 Hz are shown in brackets [ ].

	Static load	16 Hz	31.5 Hz	63 Hz	125 Hz	250 Hz	315 Hz
Pre-exposure	1.38	1.30	1.37	1.28	1.36	1.37	1.24
Pre-exposure application of force	1.46	1.44	1.44	1.27	1.37	1.52	1.30
Exposure (W_h)							
1 ms^{-2} r.m.s. [0.7]	1.22	1.30	1.31	1.13	1.25	0.97	1.15
2 ms^{-2} r.m.s.[1.5]	1.10	1.33	1.26	1.09	1.08	1.24	1.00
3 ms^{-2} r.m.s.[2.2]	1.24	1.24	1.19	0.93	1.03	0.98	0.90
4 ms^{-2} r.m.s.[2.9]	1.27	1.36	1.18	1.13	0.90	0.97	0.86
5 m^{-2} r.m.s.[3.7]	1.33	1.22	1.12	0.94	0.89	0.93	0.76
6 ms^{-2} r.m.s.[4.4]	1.35	1.00	1.03	1.05	0.82	0.92	0.88
7 ms^{-2} r.m.s.[5.1]	1.39	1.21	1.19	0.96	0.73	1.00	0.64
8 ms^{-2} r.m.s.[5.9]	1.52	1.04	1.02	0.92	0.85	0.84	0.56
9 ms^{-2} r.m.s.[6.6]	1.28	1.03	0.97	0.97	0.62	0.87	0.76
10 ms^{-2} r.m.s.[7.3]	1.35	0.78	0.97	0.75	0.80	0.90	0.60
11 ms^{-2} r.m.s.[8.1]	1.20	1.10	1.08	1.05	0.51	0.64	0.84
12 ms^{-2} r.m.s.[8.8]	1.16	0.79	1.03	0.79	0.64	0.60	0.71
13 ms^{-2} r.m.s.[9.5]	1.35	1.01	1.02	0.86	0.64	0.63	0.68
14 ms^{-2} r.m.s.[10.3]	1.23	1.13	1.06	0.67	0.61	0.54	0.61
15 ms^{-2} r.m.s.[11.0]	1.36	0.61	0.96	0.66	0.45	0.60	0.37
Post-exposure application of force	1.38	0.87	0.94	0.85	0.71	0.70	0.73

7.3.1 Finger blood flow during pre-exposure period

In all conditions, in the exposed finger, the unexposed ipsilateral finger and the unexposed contralateral finger, there were no significant changes in FBF over the 10 measurements obtained during the 10-minute pre-exposure period (p>0.1; Friedman), except in the exposed right middle finger at 125 Hz (p=0.023) and 250 Hz (p=0.054).

There were no significant differences in median pre-exposure finger blood flow across the seven conditions (p>0.1; Friedman) in any finger.

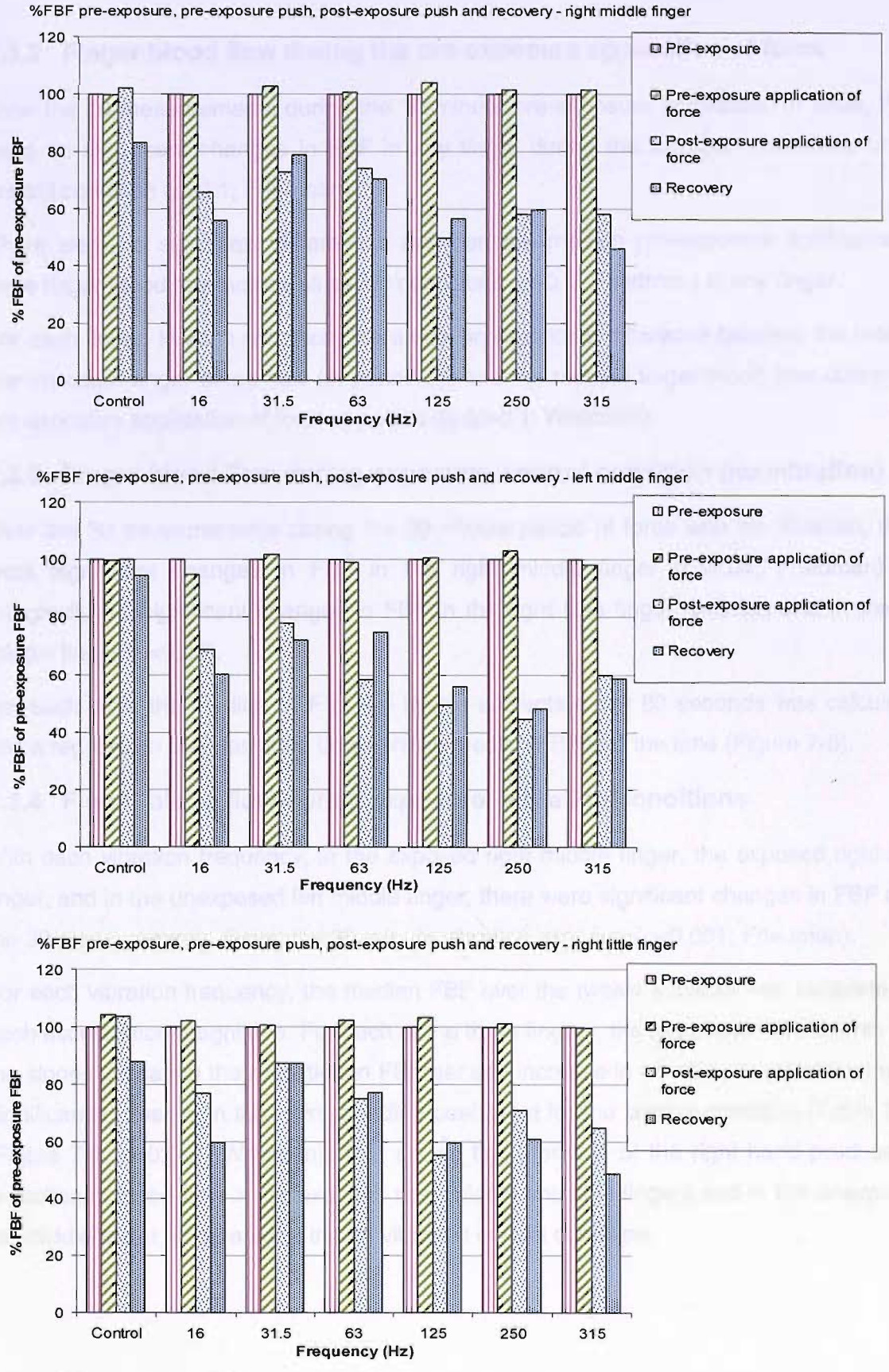


Figure 7-4 Median %FBF measured in the exposed middle right and little fingers and the non-exposed left middle finger over four of the five experimental periods (pre-exposure, pre-exposure application of force, post-exposure application of force, recovery) for the control condition and for the experimental sessions with exposure to vibration at 16, 31.5, 63, 125, 250 and 315 Hz.

7.3.2 Finger blood flow during the pre-exposure application of force

Over the 10 measurements during the 10-minute pre-exposure application of force, there were no significant changes in FBF in any finger during the vibration conditions or the control condition ($p>0.1$; Friedman).

There were no significant differences between the median pre-exposure application of force finger blood flow across all seven conditions ($p>0.1$; Friedman) in any finger.

For each finger, in each condition, there was no significant difference between the median pre-exposure finger blood flow (in period (i)) and the median finger blood flow during the pre-exposure application of force in period (ii) ($p>0.1$; Wilcoxon).

7.3.3 Finger blood flow during exposure: control condition (no vibration)

Over the 30 measurements during the 30-minute period of force with no vibration, there were significant changes in FBF in the right middle finger ($p=0.04$; Friedman) but marginally not-significant changes in FBF in the right little finger ($p=0.09$) and in the left middle finger ($p=0.08$).

For each digit, the median FBF of the twelve subjects every 60 seconds was calculated and a regression line was fitted between the median FBF and the time (Figure 7-5).

7.3.4 Finger blood flow during exposure: vibration conditions

With each vibration frequency, in the exposed right middle finger, the exposed right little finger, and in the unexposed left middle finger, there were significant changes in FBF over the 30 measurements during the 30-minute vibration exposure($p<0.001$; Friedman).

For each vibration frequency, the median FBF over the twelve subjects was calculated at each acceleration magnitude. For each of the three fingers, the regression coefficients (i.e. the slopes indicating the reduction in FBF per unit increase in vibration acceleration) were significantly lower than the corresponding coefficient for the control condition (Table 7-3). (Figure 7-5; $p<0.001$; Wilcoxon). This shows that vibration of the right hand produced a reduction in blood flow in the exposed right middle and little fingers and in the unexposed left middle finger, compared to the no vibration control condition.

For all three fingers, there was a highly significant difference between the regression slopes for the seven conditions ($p<0.001$; Friedman). For the exposed right middle finger, the slope for 125 Hz vibration was significantly greater than for 31.5 ($p=0.008$; Wilcoxon) and 63 Hz ($p=0.041$ Wilcoxon) and marginally non-significantly greater than the slope for 250 Hz ($p=0.084$; Wilcoxon). The slope for 16 Hz was marginally non-significantly greater than the slope for 31.5 Hz ($p=0.084$; Wilcoxon).

For the exposed right little finger, the slope for 125 Hz was significantly greater than for 31.5 ($p=0.050$ Wilcoxon), 63 Hz ($p=0.034$) and 250 Hz ($p=0.004$). The slopes for 16 Hz and 315 Hz were significantly greater than the slope for 31.5 Hz vibration ($p=0.05$ and $p=0.023$, respectively).

For the unexposed left middle finger, the slope for 31.5 Hz was significantly less than for 250 ($p=0.037$ Wilcoxon) and 315 Hz ($p=0.002$) and marginally non-significantly less than the slope for 16 Hz ($p=0.071$) and 125 Hz ($p=0.071$).

The FBF slopes of were compared across the three fingers at each frequency. There was no significant difference in slope between fingers ($p>0.1$; Friedman), except at 125 Hz ($p=0.024$). At 125 Hz, the slope for the exposed right middle finger was significantly greater than the slope for the unexposed left middle finger ($p=0.023$; Wilcoxon), and the slope for the right little finger was marginally non-significantly greater than the slope for the unexposed left middle finger($p=0.075$; Wilcoxon).

Table 7-3 Slopes for all three fingers for the six vibration conditions and the no-vibration control condition (rate of change in median %FBF with increasing vibration magnitude at each frequency)

	Condition						
Finger	Control	Frequency (Hz)					
		16	31.5	63	125	250	315
Right middle	0.256	-1.338	-0.860	-1.099	-2.104	-1.398	-1.205
Right little	-0.054	-1.013	-0.608	-1.204	-1.341	-1.409	-1.032
Left middle	-0.126	-1.143	-0.464	-0.977	-1.800	-1.131	-0.870

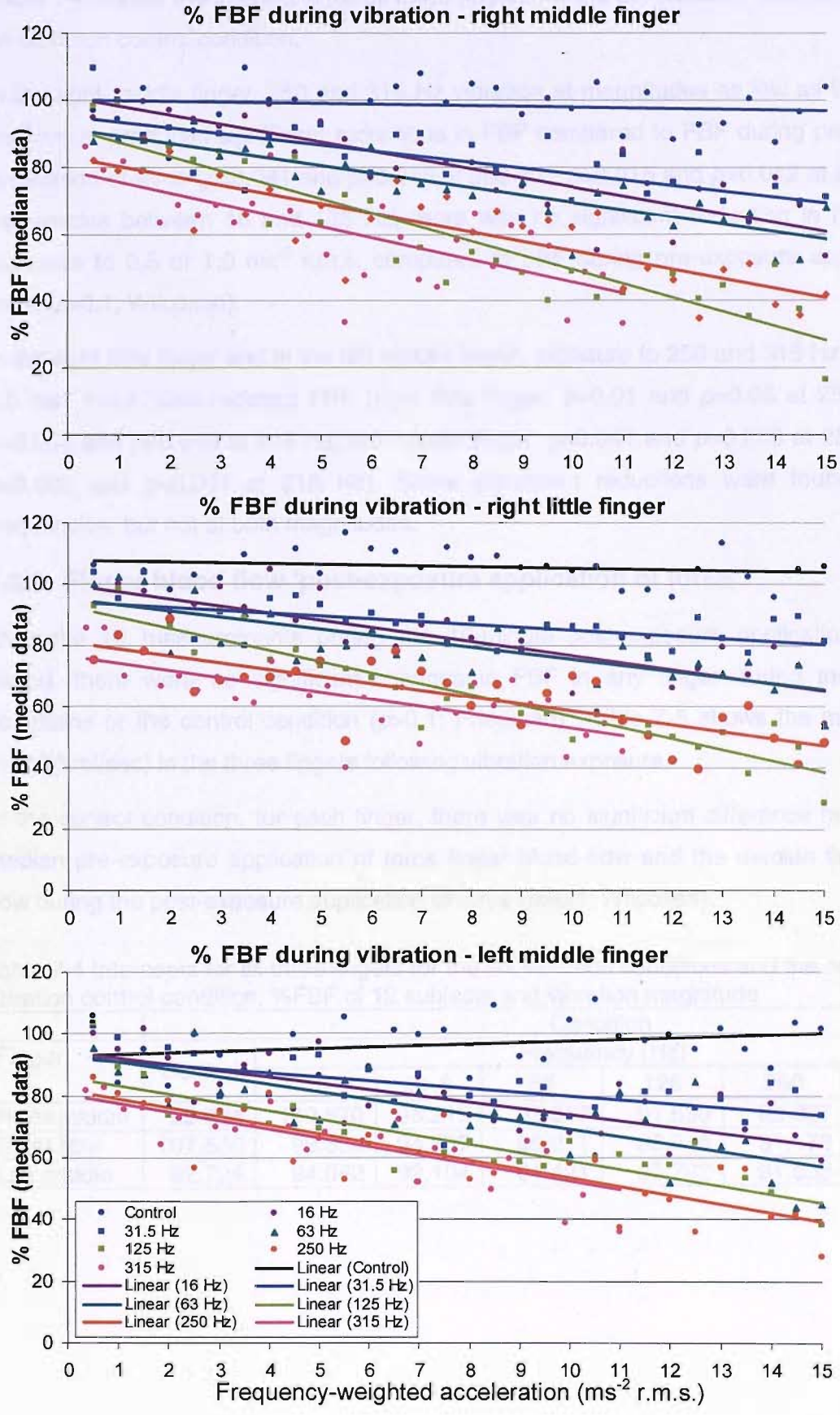


Figure 7-5 Least squares linear regressions and median percentage finger blood flow (%FBF) measured in the exposed middle right and little fingers and the non-exposed left middle finger during vibration exposure at 16, 31.5, 63, 125, 250 and 315 Hz 0 to 15 ms^{-2} r.m.s. (frequency-weighted) and 0 to 11 ms^{-2} r.m.s. (frequency-weighted) at 315 Hz and during the no-vibration control condition

Table 7-4 shows the intercepts for all three fingers for the six vibration conditions and the no-vibration control condition.

In the right middle finger, 250 and 315 Hz vibration at magnitudes as low as 0.5 and 1.0 ms^{-2} r.m.s. produced significant reductions in FBF compared to FBF during pre-exposure application of force (p=0.041 and p=0.015 at 250 Hz; p=0.015 and p=0.012 at 315 Hz). At frequencies between 16 and 125 Hz, there was no significant reduction in FBF during exposure to 0.5 or 1.0 ms^{-2} r.m.s. compared to FBF during pre-exposure application of force (p>0.1; Wilcoxon).

In the right little finger and in the left middle finger, exposure to 250 and 315 Hz at 0.5 and 1.0 ms^{-2} r.m.s. also reduced FBF (right little finger: p=0.01 and p=0.05 at 250 Hz, and p=0.034 and p=0.010 at 315 Hz; left middle finger: p=0.041 and p=0.008 at 250 Hz, and p=0.002 and p=0.004 at 315 Hz). Some significant reductions were found at other frequencies, but not at both magnitudes.

7.3.5 Finger blood flow 'post-exposure application of force'

Over the 10 measurements during the 10-minute post-exposure application of force period, there were no significant changes in FBF in any finger during the vibration conditions or the control condition (p>0.1; Friedman). Table 7-5 shows the median FBF (ml/100 ml/sec) in the three fingers following vibration exposure.

In the control condition, for each finger, there was no significant difference between the median pre-exposure application of force finger blood flow and the median finger blood flow during the post-exposure application of force (p>0.1; Wilcoxon).

Table 7-4 Intercepts for all three fingers for the six vibration conditions and the no-vibration control condition. %FBF of 12 subjects and vibration magnitude

Finger	Condition						
	Control	Frequency (Hz)					
		16	31.5	63	125	250	315
Right middle	99.634	100.870	95.215	93.217	91.539	82.927	78.672
Right little	107.530	99.634	94.307	95.211	92.545	81.178	76.447
Left middle	92.724	94.082	92.104	91.421	85.792	81.553	80.419

Table 7-5 Median FBF (ml/100 ml/sec) in three fingers following vibration exposure

Period following vibration exposure	Finger	Frequency (Hz)						
		Control	16 Hz	31.5 Hz	63 Hz	125 Hz	250 Hz	315 Hz
Post-exposure application of force	Right middle	1.388	0.865	0.933	0.851	0.701	0.691	0.726
	Left middle	1.269	0.917	0.939	0.731	0.672	0.458	0.811
	Right little	1.312	0.892	1.023	0.887	0.701	0.780	0.674
Recovery	Right middle	1.155	0.784	1.010	0.866	0.806	0.751	0.595
	Left middle	1.181	0.825	0.936	0.890	0.750	0.567	0.715
	Right little	1.082	0.810	1.053	0.945	0.734	0.703	0.557

After exposure to any of the six vibration frequencies, the median blood flow in each of the three fingers was significantly lower during post-exposure application of force than during pre-exposure application of force (right middle finger: $p<0.003$; right little finger: $p<0.012$; left middle finger: $p<0.006$).

For all fingers, during post-exposure application of force, the median finger blood flow was significantly lower after exposure to vibration than during the same period during the control condition ($p<0.05$; Wilcoxon).

For all three fingers, there was a highly significant difference in FBF between the seven conditions during post-exposure application of force ($p<0.001$; Friedman). In the exposed right middle finger, the median finger blood flow during application of force after vibration at 31.5 Hz, was significantly greater than the median finger blood flow during application of force after vibration at 125 Hz ($p=0.012$; Wilcoxon) and 315 Hz ($p=0.001$), and marginally non-significantly greater than the median finger blood flow after vibration at 250 Hz ($p=0.077$).

In the exposed right little finger, the median finger blood flow during post-exposure application of force after vibration at 31.5 Hz was significantly greater than the median finger blood flow during post-exposure application of force after vibration at 63, 125, 250 and 315 Hz ($p<0.05$; Wilcoxon). Similarly, the median finger blood flow after vibration at 16 Hz was significantly greater than the median finger blood flow after vibration at 125 Hz ($p<0.05$; Wilcoxon).

In the unexposed left middle finger, the median finger blood flow during post-exposure application of force after vibration at 31.5 Hz was significantly greater than the median finger blood flow during post-exposure application of force after vibration at 125 (p=0.05; Wilcoxon), 250 Hz (p=0.028) and 315 Hz (p=0.013). Similarly, the median finger blood flow after vibration at 16 Hz was significantly greater than the median finger blood flow after vibration at 250 Hz (p=0.045), and marginally significantly greater than the median finger blood flow after vibration at 125 Hz (p=0.099).

Within each of the six vibration conditions there was no difference in median finger blood flow between the three fingers during post-exposure application of force (p>0.1; Friedman). There was a marginally not-significantly difference between the three fingers in the control condition with no vibration (p=0.097).

7.3.6 Finger blood flow during recovery (i.e. following the removal of push force)

Over the 10 measurements during the 10-minute recovery period, there were no significant changes in FBF in any finger during the vibration conditions or the control condition (p>0.1; Friedman).

In the control condition, for each finger, the median finger blood flow during recovery was significantly lower than the median finger blood flow during the pre-exposure, pre-exposure application of force, and the post-exposure application of force (p<0.05; Wilcoxon), except for the right little finger comparing median FBF during pre-exposure with median FBF during recovery.

In the vibration conditions, for each finger, the median finger blood flow during the recovery was significantly lower than the median finger blood flow during the pre-exposure and pre-exposure application of force (p<0.05; Wilcoxon). However, median finger blood flow during the recovery was not significantly different from the median finger blood flow during the post-exposure application of force (p>0.1; Wilcoxon).

For all fingers, the median finger blood flow during recovery in the vibration conditions was significantly lower than the median blood flow during the recovery in the control condition (p<0.05; Wilcoxon), except after exposure to 31.5 Hz.

For all three fingers, there were significant differences in FBF between the seven conditions during the recovery period (p=0.061 in the right middle finger and p<0.001 in the other two fingers; Friedman). In the exposed right middle finger the median finger blood flow during recovery at 31.5 Hz was greater than the median finger blood flow during

recovery at 125 and 250 Hz ($p<0.05$; Wilcoxon), but not significantly greater than the median finger blood flow at 63 Hz ($p=0.099$; Wilcoxon) or 315 Hz ($p=0.084$; Wilcoxon).

In the exposed right little finger the median finger blood flow during recovery at 31.5 Hz was significantly greater than the median finger blood flow during recovery at 16, 125, 250 and 315 Hz ($p<0.05$; Wilcoxon) but not significantly greater than the median finger blood flow at 63 Hz (p=0.071; Wilcoxon).

In the unexposed left middle finger the median finger, blood flow during recovery at 31.5 Hz was significantly greater than the median finger blood flow during recovery at 125 and 250 Hz ($p<0.05$; Wilcoxon), but not significantly greater than the median finger blood flow at 315 Hz (p=0.099; Wilcoxon).

During the recovery, there was no difference in median finger blood flow between the three fingers within any of the seven conditions ($p>0.1$; Friedman).

7.4 DISCUSSION

7.4.1 Finger blood flow during vibration exposure

Vibration applied to the palm of the hand at frequencies in the range of 16 to 315 Hz, with an increasing frequency-weighted acceleration from 0 to 15 ms^{-2} r.m.s. (0 to 11 ms^{-2} r.m.s. at 315 Hz), caused reductions in finger blood flow on the exposed and unexposed hand compared with pre-exposure measures. Vibration also reduced finger blood flow in all fingers compared to finger blood flow during a control condition with force but no vibration.

The reductions in finger blood flow in this study during and after vibration are consistent with the reductions in finger blood flow, in the palm contact conditions in Chapter 6.

During vibration, finger blood flow in all fingers reduced progressively with increases in the magnitude of vibration. The findings of this study are consistent with those of Bovenzi *et al.* (1999) who found that FBF in exposed and unexposed digits was inversely proportional to vibration magnitude in the range of 0.69 to 7.75 ms^{-2} r.m.s. (weighted) at 125 Hz. The present study investigated greater vibration magnitudes than Bovenzi *et al.* (1999) but did not find greater reductions in FBF. The greater reduction in FBF in the Bovenzi *et al.* (1999) study may have arisen because of reductions in FBF caused by force to the exposed hand. The reductions in finger blood flow during vibration in this study are consistent with the reductions in finger blood flow in the palm contact conditions in Chapter 6.

With the whole hand exposed to vibration and a force of 10 N (compared to palm contact and 2 N in the present study), Bovenzi *et al.* (2000) found that during vibration 16 Hz

produced less reduction in FBF in exposed and non-exposed digits than 31.5 to 250 Hz, when using a constant frequency-weighted acceleration of 5.5 ms^{-2} r.m.s. The experiment presented in Chapter 7 shows a frequency-dependence in the reduction of finger blood flow in the exposed and unexposed fingers. The FBF in the exposed right middle finger was reduced during exposure to 125 Hz compared to 31.5 and 63 Hz and, perhaps, 250 Hz. In the experiment in Chapter 7 a similar response was seen in the exposed right little finger, with a significant reduction in flow with 125 Hz compared to 250 Hz. In the unexposed left middle finger, the trends were similar.

Other studies have found varying vascular responses to vibration frequency in the exposed hand. Welsh (1980) found a greater reduction in flow during exposure to 120 Hz than 40, 80, 160 and 200 Hz when using constant amplitude vibration. Furuta *et al.* (1991) found reduced finger blood flow during exposure to vibration at 31.5, 63, 250 and 500 Hz compared to blood flow during exposure to 16, 125 and 1000 Hz with acceleration magnitudes of 10 and 50 ms^{-2} r.m.s. Like the current study, Furuta *et al.* (1991) exposed the palm, but used intermittent vibration of 1-minute duration followed by 3-minutes of no-vibration.

The present results show that low magnitudes of vibration (0.5 and 1.0 ms^{-2} r.m.s.) at 250 and 315 Hz can reduce finger blood flow on both the exposed and the unexposed hand, whereas 16 to 125 Hz vibration did not significantly reduce finger blood flow at these magnitudes. This may suggest the involvement of one or more vibrotactile channels in the acute vascular response to vibration.

A reduction in FBF on both vibration-exposed and unexposed hands during vibration has been reported previously (Bovenzi *et al.*, 1998, 1999, 2000, 2006; Griffin *et al.*, 2006) and hypothesized as being due to a central sympathetic vasomotor reflex (Bovenzi *et al.*, 2000). In contrast to previous studies, the present study found the reduction in FBF to be similar in exposed and unexposed hands, except at 125 Hz where the exposed hand exhibited a stronger response than the unexposed hand. Previous research, mainly with 125 Hz vibration, has indicated a stronger reduction in FBF on the exposed hand (Bovenzi *et al.*, 1998, 1999, 2000, 2006; Griffin *et al.*, 2006). The difference in response between exposed and unexposed hands has been attributed to local physiological factors in the hand in contact with the vibration (Bovenzi *et al.*, 2000). The push force, location of contact, and area of contact with the exposed hand may influence FBF in the exposed hand (Chapter 6; Bovenzi *et al.*, 2006; Griffin *et al.*, 2006). In the present study, only the palm was in contact with the vibrating platform and a push force of only 2 N was applied,

so as to minimise the influence of force on FBF. A difference between exposed and unexposed hands in some studies may have arisen from local effects of force on FBF.

7.4.2 Finger blood flow after vibration exposure

Following vibration, the present study found continued reduction in FBF on the exposed and unexposed hand, consistent with the results obtained with the palm conditions in Chapter 6. In contrast, Bovenzi *et al.* (1998, 1999, 2000) found that the simultaneous cessation of vibration and force resulted in an immediate vasodilation. Possibly the vascular response to vibration is prolonged vasoconstriction, but cessation of force may relieve compression of some digital arteries and result in a temporary increase in blood flow, with the effect varying according to the location of application of force.

A 2 N force applied to the palm did not affect finger blood flow in the exposed or unexposed fingers during the 50-minute application of the force in the control condition of the experiment in Chapter 7. However, application of force at other locations on the palm, or the application of force to the fingers, may reduce blood flow in fingers of the hand applying force (Chapter 6; Bovenzi *et al.*, 2006; Griffin *et al.*, 2006). The removal of force after 50 minutes resulted in a small reduction in FBF in fingers on both the exposed and the non-exposed hand. It would seem appropriate to consider force when measuring finger blood flow and when assessing risks from occupational exposures to hand-transmitted vibration.

Bovenzi *et al.* (2000) found a delayed frequency-dependent reduction in finger blood flow after the end of exposure to vibration. In the present study, vibration caused continued reductions in finger blood flow immediately after vibration and for the duration of the recovery period, compared with pre-exposure measures. As in Bovenzi *et al.* (2000) and Chapter 6, the reduction in blood flow in this study was frequency-dependent, with lower frequencies causing less reduction in flow than higher frequencies in both exposed and unexposed fingers.

In this study, the reduction in blood flow after the end of vibration was similar in the exposed and unexposed hands.

7.5 CONCLUSION

With equal frequency-weighted vibration magnitudes at frequencies from 16 to 315 Hz, vasoconstriction depends on the frequency of vibration, with evidence of greater reductions in the region of 125 Hz. With vibration at 250 and 315 Hz, vibration magnitudes sometimes considered 'low' produced an immediate reduction in finger blood flow on both exposed and non-exposed hands. Increasing the vibration magnitude increased

vasoconstriction. Finger blood flow after the cessation of vibration also depends on vibration frequency, with frequency-weighted acceleration of the higher frequencies causing a greater reduction than lower frequencies. Both during and after exposure to hand-transmitted vibration, the vasoconstriction was similar in fingers of the exposed and unexposed hands.

CHAPTER 8

THE DEPENDENCE OF FINGER BLOOD FLOW ON VIBRATION OF ONE OR TWO HANDS

8.1 INTRODUCTION

Many users of vibrating tools expose two hands to vibration. Experimental studies investigating the dependence of finger blood flow on vibration have exposed one hand to vibration and measured changes in finger blood flow in both hands. Without a confounding effect of force, vibration to one hand reduces blood flow equally in the exposed hand and the unexposed contralateral hand (Chapters 6 and 7), giving confidence to the hypothesis that vibration activates a centrally mediated mechanism. The characteristics of the mechanism controlling vasoconstriction are not well understood and, at present, can only be described in terms of the vascular response to the vibration stimulus. Chapters 6 and 7 have outlined the dependence of finger blood flow on vibration magnitude and frequency with vibration exposure to only one hand. Vibration of two hands may not show the same dependence on magnitude and frequency as vibration of one hand.

The reduction in finger blood flow (FBF) during vibration exposure is reported to be dependent on vibration magnitude (Bovenzi *et al.*, 1999; Chapters 5 to 7). In Chapters 5 to 7, one hand was exposed to vibration and it was found that changing the vibration magnitude changed the strength of vasoconstriction proportionally in both hands. The mechanism triggering the vasoconstriction in both hands appears to be sensitive to changes in vibration magnitude. It is not known whether the reduction in blood flow is greater during exposure of two hands than during exposure of one hand – it could be considered that vibrating two locations doubles the vibration dose.

The reduction in FBF during vibration depends on vibration frequency. The experiments in Chapters 6 and 7 found a greater reduction in blood flow at higher frequencies than at lower frequencies within the range of 16 to 315 Hz with magnitudes from 0 to 15 ms^{-2} r.m.s. The relationship between frequency and reduction in flow is not simple: doubling the frequency of vibration to one hand did not double the reduction in blood flow at a particular magnitude (Chapter 7). It may be that the degree of vasoconstriction at each frequency is pre-determined by, for example, a vibrotactile threshold.

In Chapters 6 and 7, immediately after the end of vibration exposure, the blood flow continued to be reduced, with a greater reduction after exposure to higher frequencies than after exposure to lower frequencies (between 16 to 315 Hz with magnitudes from 0 to 15 ms^{-2} r.m.s.). After the end of vibration exposure, Bovenzi *et al.* (1999) found delayed vasoconstriction that was partly dependent on the vibration magnitude. Consistent with the studies in Chapters 6 and 7, Bovenzi *et al.* (2001) found the vasoconstriction was dependent on the vibration frequency. A stronger reduction in flow may occur after vibration of two hands compared to one hand, at the same frequency and magnitude, as the input would have been doubled. Any central mediating mechanisms will have been triggered by two hands. A longer and more pronounced vasoconstriction might be expected.

The simultaneous application of force and vibration to one hand reduces finger blood flow in both the exposed hand and the contralateral hand not exposed to vibration. This suggests that the simultaneous vibration of two hands will produce a greater reduction in finger blood flow than vibration of one hand.

Previous experimental studies have found that push force and the location of application of the force can affect finger blood flow. A 20 N force applied to the palm produced a greater reduction in finger blood flow than 5 N (Griffin *et al.*, 2006). A 5 N force reduced blood flow more than a 2 N force applied to the finger (Bovenzi *et al.*, 2006). The effect of force depends on the location of application of force, with 2 N reducing finger blood flow when applied by the finger but not when applied by the palm (Chapter 6). The effect of the application of force to two locations has not been studied. The study of the application of force to two palms will test if there is a cumulative effect of force and vibration on finger blood flow.

A stronger vasoconstriction in the exposed hand than in the unexposed hand reported in previous studies can be explained by mechanical or locally acting mechanisms reducing the finger blood flow during exposure. This study investigated the simultaneous vibration of two hands.

This study investigated the influence of vibration magnitude at 31.5 and 125 Hz on finger blood flow and the effect of exposing one or two hands to force and vibration. The main hypothesis was that vibration applied to two hands would result in greater reduction in finger blood flow, both during and after exposure, than vibration applied to one hand.

8.2 METHOD

8.2.1 Subjects

Ten healthy male volunteers aged 18.7 to 51.0 years participated in the study. The subjects were students and office workers with no history of regular exposure to hand-transmitted vibration and no medical disorders known to influence finger blood flow. Subjects avoided caffeine for 2 hours prior to testing and avoided alcohol for 12 hours prior to testing.

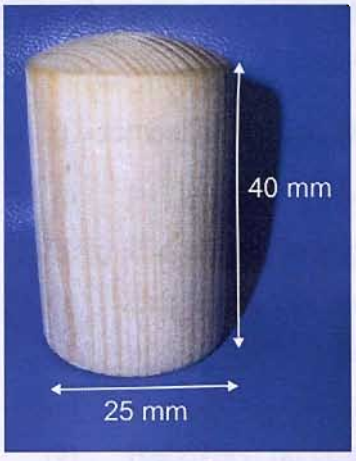


Figure 8-1 Dimensions of the cylindrical wooden platform with domed end.

8.2.2 Equipment

A Derritron VP4 electrodynamic vibrator provided vibration to the right hand. A Huntleigh force cell was attached to the vibrator table to measure the downward force exerted by the right hand. Visual feedback of a force meter allowed subjects to control their push force. To monitor vibration, an Entran 233E accelerometer was attached to a metal plate screwed to the top of the force cell.

A Derritron VP30 electrodynamic vibrator provided vibration to the left hand. A Kulite force cell was attached to the vibrator table of the VP30 to measure the downward force exerted by the left hand. Visual feedback through a second force meter allowed subjects to control the application of push force to the left hand. To monitor vibration, an Entran 233E accelerometer was attached to a metal plate screwed to the top of the force cell.

A cylindrical wooden platform with a domed end (Figure 8-1) was secured on each metal plate so that the centre of a subject's palm could be placed on the wooden platform with all fingers suspended in air (Figure 8-2).

Subjects were supine throughout the experiment with both arms and both hands supported at heart height.

Room temperature was measured using a K-type thermocouple connected to an *HVLab* thermal aesthesiometer that was accurate to 0.5°C. The thermocouple was located close to the head of the subject. Room temperature was controlled to the range 27.0°C to 28.3°C by two radiators.

8.2.3 Experimental conditions

Subjects were exposed on separate days to five sessions in which vibration at either 31.5 Hz or 125 Hz was applied to either the right hand (unilateral vibration) or to both hands (bilateral vibration).

During each session, there were five experimental periods:

(i) Pre-exposure: no push force for 10 minutes,

(ii) Pre-exposure application of force: 2 N push force for 5 minutes,

(iii) Exposure: 2 N push force with 125 Hz or 31.5 Hz vibration successively at 5.5, 11 and 22 ms^{-2} r.m.s. (unweighted) in three 5-minute intervals over 15 minutes,

(iv) Post-exposure application of force: 2 N push force for 5 minutes,

(v) Recovery: no push force for 15 minutes.

During the sessions with unilateral vibration, force was applied by the left and the right hand in the second, third and fourth period and vibration was applied to the right hand during the third period. The left hand was not exposed to vibration during this session.

During the sessions with bilateral vibration, force was applied by both the left and right hand

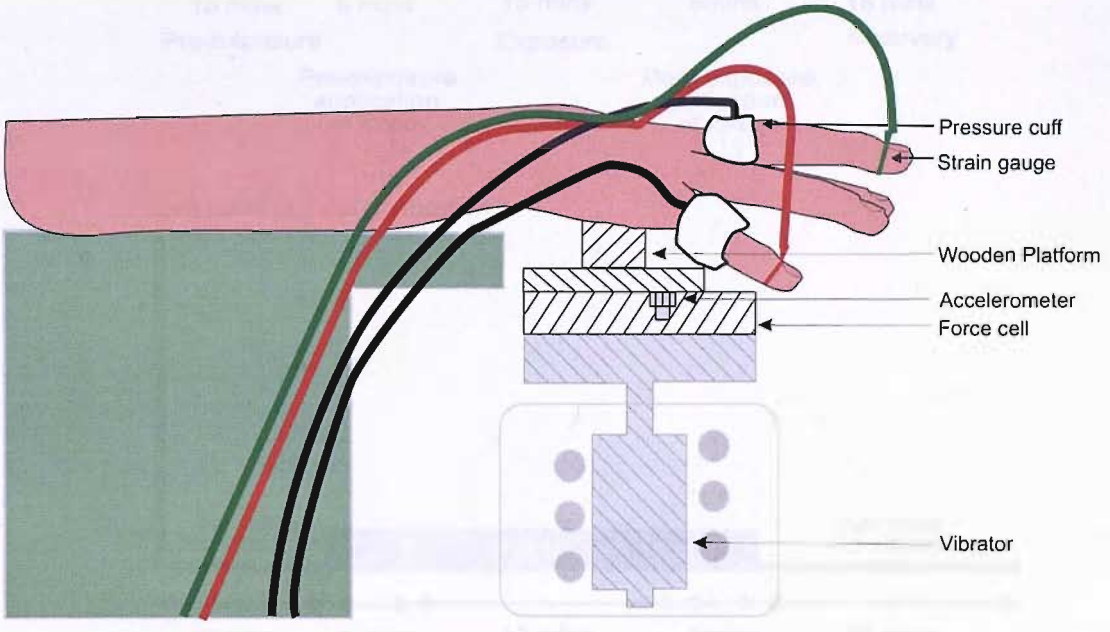


Figure 8-2 Experimental set-up for generating and measuring the vibration, controlling the contact force at the right palm and measuring finger blood flow on the right middle finger. A similar second set of equipment was used to generate and measure vibration applied to the left hand, controlling the contact force at the left palm and measuring finger blood flow in the left middle finger.

in the second, third, and fourth periods and vibration was applied to both the left and right hands during the third period.

Sinusoidal vibration was produced in the vertical direction at one of the combinations of vibration frequencies and acceleration magnitudes shown in Table 8-1.

There was an acclimatisation period of 15 minutes prior to each session. Each experimental session therefore lasted 65 minutes.

Figure 8-3 illustrates the five periods of the unilateral vibration condition.

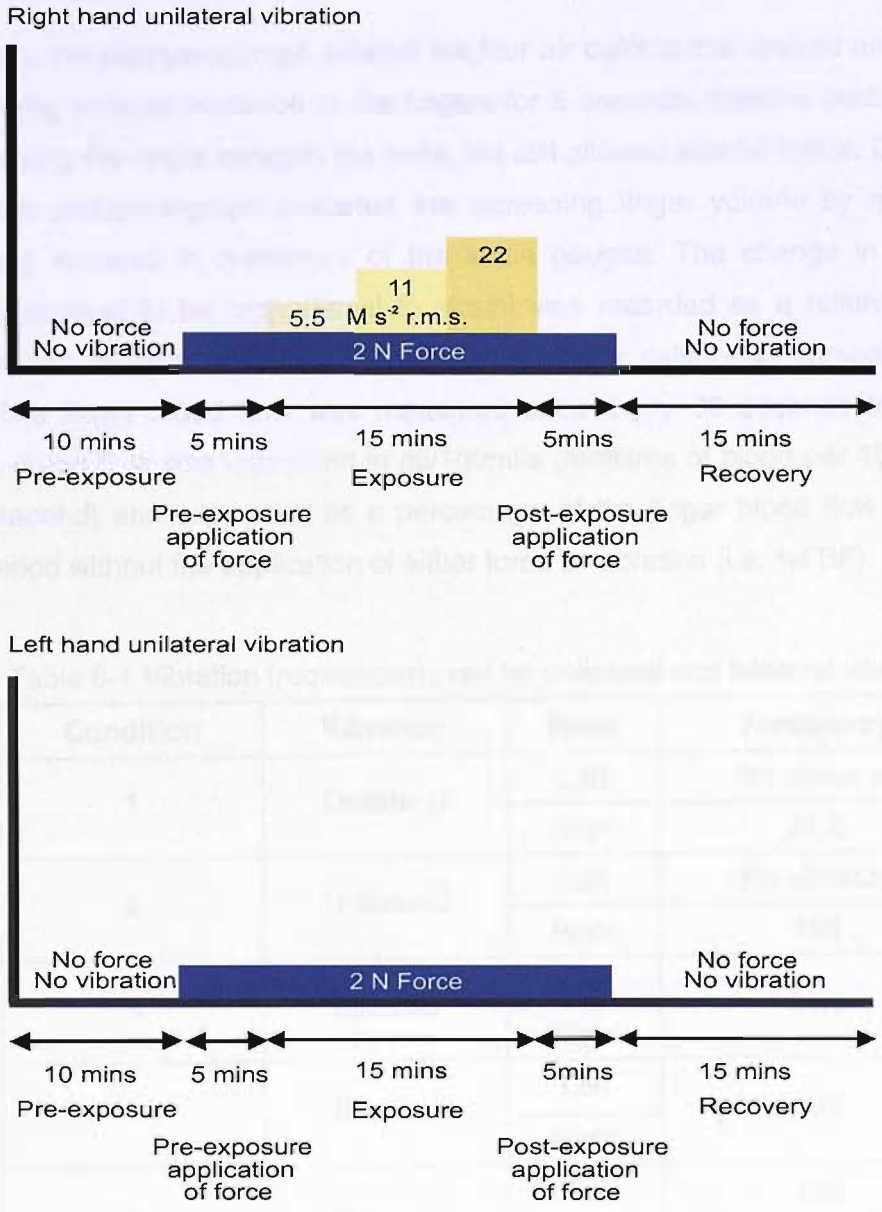


Figure 8-3 The sequence of push force and vibration exposure during the five experimental periods of the unilateral vibration condition: pre-exposure, pre-exposure application of 2 N push force, vibration exposure at 5.5, 11 and 22 ms^{-2} r.m.s. (unweighted), post-exposure application of 2 N, and recovery following cessation of vibration and push force.

8.2.4 Measures of finger circulation

Finger blood flow was measured using strain gauge venous occlusion plethysmography according to the technique proposed by Greenfield *et al.* (1963).

Flexible plastic cuffs were fitted snugly around the proximal phalanges of the right and left middle and little fingers. The soft plastic tubes of the four cuffs were connected to a plethysmograph (*HVLab* Multi-channel). A mercury-in-silastic strain gauge was positioned between the nail and the distal interphalangeal joint of each digit. The strain gauge size was chosen so that it was in slight extension. The same strain gauge was used for both experimental sessions with a subject.

On instruction, the plethysmograph inflated the four air cuffs to the desired air pressure, 60 mmHg, applying venous occlusion to the fingers for 5 seconds. Venous occlusion stopped the blood leaving the finger beneath the cuffs, but still allowed arterial inflow. During venous occlusion, the plethysmograph indicated the increasing finger volume by measuring the corresponding increase in resistance of the strain gauges. The change in strain gauge resistance (assumed to be proportional to strain) was recorded as a relative percentage change from the baseline resistance measured during a calibration immediately prior to occlusion. The finger blood flow was measured once every 60 seconds throughout the experiment. Blood flow was measured in ml/100ml/s (millilitres of blood per 100 millilitres of tissue per second) and expressed as a percentage of the finger blood flow during a pre-exposure period without the application of either force or vibration (i.e. %FBF).

Table 8-1 Vibration frequencies used for unilateral and bilateral vibration.

Condition	Vibration	Hand	Frequency
1	Unilateral	Left	No vibration
		Right	31.5
2	Unilateral	Left	No vibration
		Right	125
3	Bilateral	Left	31.5
		Right	
4	Bilateral	Left	125
		Right	
5	Bilateral	Left	125
		Right	31.5

Finger skin temperature was measured by a thermocouple attached by micro pore tape to the distal phalanx of the right middle finger.

8.2.5 Experimental Procedure

Initially, a supine subject was acclimatised for 15 minutes with his hands supported alongside the body at about the level of the heart. Subsequently, during the pre-exposure period, finger blood flow was measured every minute for 10 minutes while the subject remained in the same posture adopted during the acclimatisation period. The hands of the subject were supported by wooden boxes at the same height as when they were later exposed to vibration.

To apply a push force, the experimenter positioned the hands with the centre of each palm in contact with the dome of the wooden platform secured to each vibrator. The hands were in comfortable postures with the fingers suspended without contact. When required, the subject applied a downward force of 2 N with both palms, and maintained this force continuously for 25 minutes.

During exposure to vibration, either the right hand or both the right and the left hand were vibrated. Vibration commenced at 5.5 ms^{-2} r.m.s. for 5 minutes, then increased to 11 ms^{-2} r.m.s. for 5 minutes, and finally increased to 22 ms^{-2} r.m.s. These magnitudes correspond to frequency-weighted magnitudes of 2.75, 5.5 and 11 ms^{-2} r.m.s with 31.5 Hz vibration and 0.70, 1.41, 2.82 ms^{-2} r.m.s with 125 Hz vibration. The vibration then stopped.

After the vibration had ceased, the force was held for a further 5 minutes. At the 35^{th} minute of the session, the subject released the push force from both hands while keeping the hands in the same posture. The experimenter then repositioned the hands so that they were again supported alongside the body at heart level, as during the pre-exposure period.

8.2.6 Statistical Methods

Data were analysed using the Statistical Package for the Social Sciences (SPSS) version 14.0. Non-parametric statistical techniques, Friedman two-way analysis of variance and Wilcoxon matched-pairs signed ranks tests, were employed to investigate differences between repeated measures. The criterion for statistical significance was $p<0.05$.

8.3 RESULTS

Table 8-2 shows the median and inter-quartile range of finger blood flow measured in the right and left middle and little fingers during the five periods of each experimental session: pre-exposure, pre-exposure application of force, vibration exposure to one or two hands, post-exposure application of force, and recovery after vibration and force had ceased.

Table 8-2 Median finger blood flow measured during pre-exposure, pre-exposure application of force, vibration exposure to one or two hands of 5.5, 11 and 22 ms^{-2} r.m.s. (unweighted), post-exposure application of force and during recovery after vibration and force has ceased.

Condition	Freq-uency (Hz)	Digit	Pre-exposure	Pre-exposure application of force	Vibration 5.5 ms^{-2} r.m.s.	Vibration 11 ms^{-2} r.m.s.	Vibration 22 ms^{-2} r.m.s.	Post-exposure application of force	Recovery
			FBF (mm100ml/sec)						
1 Vibration right hand	31.5	Right middle	1.26	1.14	1.20	1.03	1.11	1.15	0.83
		Right little	1.17	1.07	1.36	1.00	0.85	0.96	0.80
		Left Middle	1.31	1.17	1.17	1.05	1.11	1.17	0.88
		Left Little	1.09	1.08	1.05	0.90	0.94	1.07	0.90
2 Vibration right hand	125	Right middle	1.26	1.16	0.95	0.84	0.80	0.89	0.80
		Right little	1.17	1.09	0.83	0.67	0.68	0.86	0.78
		Left middle	1.30	1.17	1.01	0.89	0.78	0.92	0.87
		Left Little	1.16	1.08	0.80	0.84	0.77	0.92	0.76
3 Vibration right and left hands	31.5	Right middle	1.20	1.20	1.02	0.93	0.79	0.79	0.95
		Right little	1.00	0.95	0.96	0.92	0.69	0.69	0.88
		Left Middle	1.23	1.23	0.90	0.83	0.80	0.93	0.85
		Left Little	0.97	0.88	0.93	0.71	0.63	0.55	0.79
4 Vibration right and left hands	125	Right middle	1.23	1.23	0.90	0.83	0.79	0.93	0.85
		Right little	1.07	1.00	0.87	0.81	0.57	0.81	0.79
		Left middle	1.37	1.15	1.05	0.86	0.86	0.84	0.73
		Left Little	1.13	1.06	0.89	0.70	0.80	0.86	0.78
5 Vibration right and left hands	125	Right middle	1.30	1.28	1.10	0.88	0.95	0.78	0.85
		Right little	1.13	1.11	0.97	0.76	0.84	0.91	0.86
	31.5	Left Middle	1.34	1.22	1.12	0.83	0.80	0.91	0.95
		Left Little	1.16	1.14	0.99	0.80	0.78	0.88	0.86

8.3.1 Finger blood flow during 'pre-exposure'

The finger blood flow was expressed as a percentage of the pre-exposure finger blood flow (i.e. %FBF). Figure 4 shows the %FBF in the right and left middle and little fingers during the pre-exposure, pre-exposure application of force, vibration exposure, the post-exposure application of force, and recovery periods of the five experimental conditions.

During the pre-exposure periods (before sessions with both unilateral and bilateral vibration), there were no significant differences over the 10 finger blood flow measurements in the left or right, middle or little fingers ($p > 0.05$; Friedman).

There were no significant differences in pre-exposure finger blood flow across the five conditions ($p<0.1$: Friedman) in any finger.

There was no significant difference between blood flow in the left or right middle fingers, before unilateral or bilateral vibration at 125 Hz or in condition (v) with both 31.5 and 125 Hz vibration ($p > 0.09$). Before unilateral and bilateral vibration at 31.5 Hz, blood flow in the middle fingers was reduced compared to blood flow in the pre-exposure period ($p < 0.05$).

In the little fingers there was no significant difference in blood flow between the left and right little fingers in either the unilateral or bilateral sessions ($p>0.1$), except for lower FBF in the left little than in the right middle finger in the unilateral session at 31.5 Hz ($p=0.037$).

8.3.2 Finger blood flow during 'pre-exposure application of force'

During pre-exposure application of force, there were no significant differences over the five finger blood flow measurements in either the left or right, middle or little fingers ($p>0.05$; Friedman), with the exception of the left little finger before unilateral vibration at 31.5 Hz ($p=0.042$) and the right middle finger before bilateral vibration at 125 Hz ($p =0.045$).

The application of force by the left and right palms tended to reduce FBF in the fingers compared to the FBF during the pre-exposure period, but most reductions were not statistically significant ($p>0.1$) (Figure 4). A significant reduction in FBF with the application of force was found in the right middle finger before unilateral vibration at 31.5 Hz ($p=0.022$), in the right little finger before bilateral vibration at 31.5 Hz ($p=0.038$), and in the left middle finger before bilateral vibration at 125 Hz ($p=0.047$).

In all five conditions, there was no significant difference in finger blood flow between the right and left middle fingers ($p>0.1$), or between the right and left middle fingers ($p>0.1$).

There was no difference in finger blood flow prior to unilateral vibration and the finger blood flow prior to bilateral vibration, before either the sessions with 31.5 Hz vibration or the sessions with 125 Hz vibration, in any finger ($p > 0.1$).

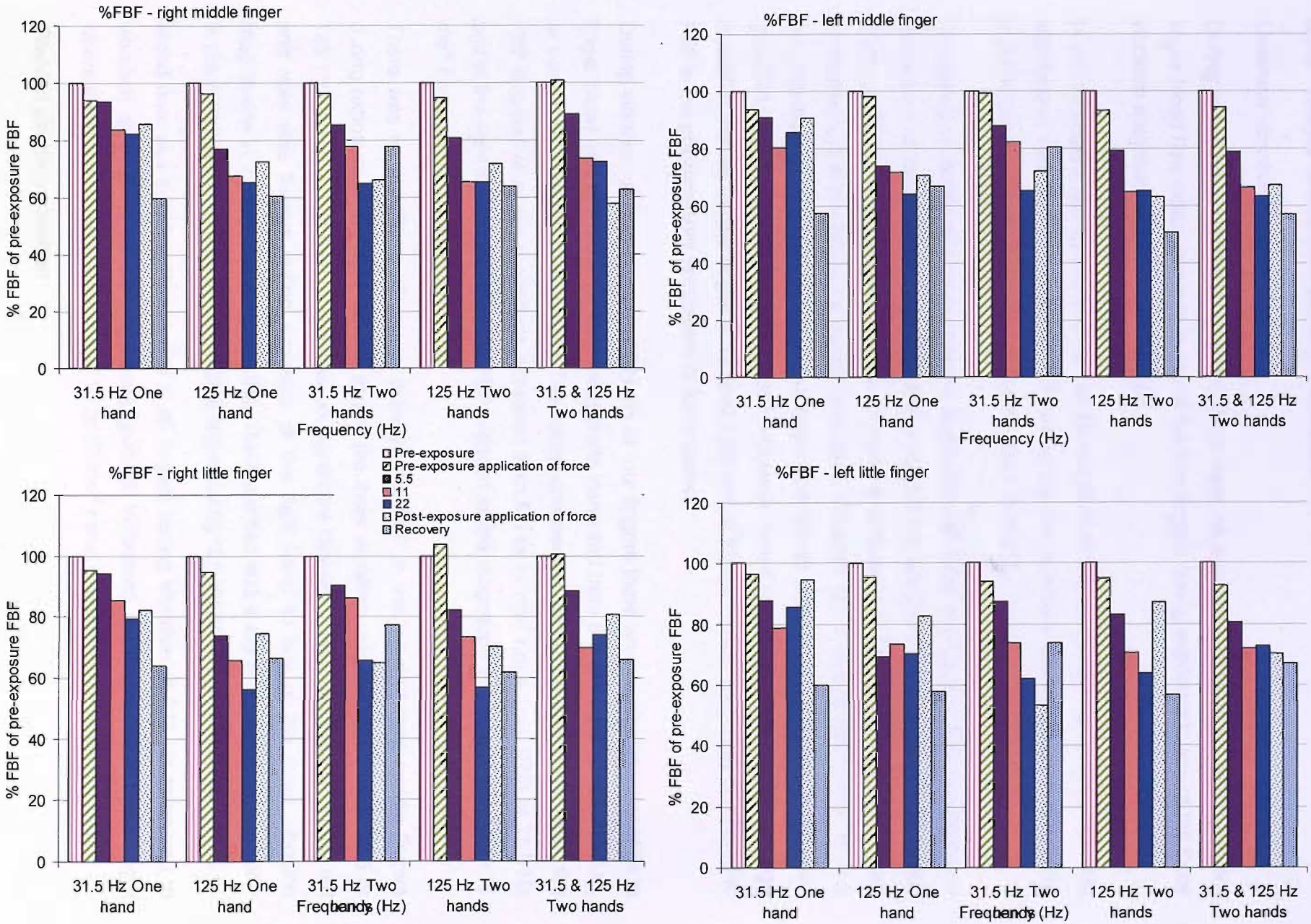


Figure 8-4 Percentage finger blood flow (%FBF) in the right and left middle and little fingers, in the pre-exposure period, the pre-exposure application of force period, during vibration exposure at 5.5, 11 and 22 ms^{-2} r.m.s. (unweighted), the post-exposure application of force period and in the recovery period, in the five experimental conditions.

8.3.3 Finger blood flow during 'exposure'

Unilateral vibration condition.

During exposure to unilateral vibration, there were no significant differences within the five finger blood flow measurements in any of the four fingers during exposure to any of the three vibration magnitudes (p>0.05; Friedman).

In all four fingers, during exposure to 125 Hz vibration at 5.5, 11 and 22 ms^{-2} r.m.s., FBF was significantly reduced compared to FBF during the pre-exposure period (p<0.01; Wilcoxon) and the 'pre-exposure application of force' period (p<0.01).

Compared to during the 'pre-exposure application of force' period and the 'pre-exposure application of force' period, vibration of 5.5 at 31.5 Hz vibration, did not affect FBF in any finger (p>0.05). The exception was a significant reduction in FBF in the left little finger compared to the pre-exposure period (p=0.037). Vibration of 11 and 22 ms^{-2} r.m.s. at 31.5 Hz, significantly reduced FBF In all four fingers compared to during the pre-exposure period ($p < 0.01$) and the 'pre-exposure application of force' period ($p < 0.01$). There was no change in FBF in the left middle finger at 11 (p=0.139) and at 22 ms^{-2} r.m.s. (p=0.169) compared to FBF in the pre-exposure application of force period.

During vibration at 31.5 Hz and 125 Hz in all four fingers there was no significant change in finger blood flow when the vibration magnitude increased from 5.5 to 11 ms^{-2} r.m.s. (p>0.1), or from 11 to 22 ms^{-2} r.m.s. (p>0.1). The exceptions were in the right middle finger when the FBF reduced when the magnitude increased from 5.5 to 11 ms^{-2} r.m.s. (p=0.028) at 31.5 Hz and in the right little finger when the FBF reduced as the magnitude increased from 5.5 to 11 ms^{-2} r.m.s. at 125 Hz (p=0.037).

There was no significant difference between the FBF in the left and right middle fingers during exposure of the right hand to any of the three vibration magnitudes at either 31.5 or 125 Hz ($p > 0.1$). Similarly, there was no significant difference between the FBF in the left and right little fingers during exposure of the right hand to any of the three vibration magnitudes at 31.5 or 125 Hz ($p > 0.05$). The exception was a significantly lower blood flow in the right little finger than in the left little finger during 125 Hz at 11 ms^{-2} r.m.s. (p=0.017).

Blood flow was significantly reduced in all fingers during vibration at 125 Hz compared to vibration at 31.5 Hz, at all magnitudes (p<0.05; Wilcoxon), except in the left little finger where there was no difference at 5.5, 11 or 22 ms^{-2} r.m.s. (p>0.05).

Bilateral vibration condition

During exposure to 31.5 and 125 Hz bilateral vibration, there was no significant difference in any finger over the five FBF measurements at any of the three vibration magnitudes ($p>0.05$; Friedman), except during bilateral vibration with 125 Hz applied to the left hand and 31.5 Hz applied to the right hand at 11 ms^{-2} r.m.s., when the left and right middle fingers were significantly variable over the 5 measurements ($p<0.05$).

Compared to during the 'pre-exposure application of force' period exposure to bilateral vibration of 5.5 ms^{-2} r.m.s. at 31.5 Hz and 125 Hz significantly reduced FBF in the middle fingers ($p<0.05$). The exception was no significant difference in the little right ($p=0.074$) or little left fingers ($p=0.114$) at 31.5 Hz compared to pre-exposure finger blood flow. Vibration of 11 and 22 ms^{-2} r.m.s. at 31.5 and 125 Hz, significantly reduced FBF in all fingers compared to the FBF during the pre-exposure period ($p < 0.01$; Wilcoxon).

Compared to during the 'pre-exposure application of force' period, vibration of 5.5 and 11 ms^{-2} r.m.s. at 31.5 Hz vibration, did not affect FBF in any finger ($p>0.05$: Wilcoxon), except in the right middle finger ($p<0.05$). However, vibration of 22 ms^{-2} r.m.s. at 31.5 Hz reduced the FBF in all fingers ($p< 0.05$), except the right little finger ($p=0.110$).

During unilateral vibration of 5.5, 11 and 22 ms^{-2} r.m.s. at 125 Hz, FBF in all fingers was significantly reduced, compared to blood flow during the 'pre-exposure application of force' period ($p< 0.01$), except in the left little finger at 11 ms^{-2} r.m.s. ($p=0.093$).

When vibrating two hands at 31.5 Hz, increasing the magnitude from 5.5 to 11 ms^{-2} r.m.s. did not change finger blood flow in any finger ($p>0.1$). There were significant reductions in FBF in all fingers when the magnitude increased from 11 to 22 ms^{-2} r.m.s. ($p< 0.05$), except in the left little finger ($p=0.074$).

Vibration of 11 ms^{-2} r.m.s. at 125 Hz applied to both hands caused a significant reduction in flow in all fingers compared to vibration at 5.5 ms^{-2} r.m.s. ($p < 0.05$), except in the left little finger ($p=0.126$). However, there was no significant change in finger blood flow in any finger when vibration increased from 11 to 22 ms^{-2} r.m.s. ($p > 0.05$), except in the right little finger. ($p=0.047$).

During exposure to both frequencies bilaterally, there was no significant difference in FBF between the left and right middle fingers ($p > 0.1$), or between the left and right little fingers ($p > 0.1$) with any of the three vibration magnitudes.

In the middle fingers and in the little fingers, there were no significant differences in FBF between bilateral vibration at 31.5 and bilateral vibration 125 Hz at any magnitude ($p>0.1$; Wilcoxon).

There was no significant difference in FBF between bilateral vibration with both hands exposed to 31.5 Hz compared to bilateral vibration with the left hand exposed to 125 Hz and the right hand exposed to 31.5 Hz, in any finger, at any magnitude ($p>0.05$).

There was no significant difference in FBF between bilateral vibration with both hands exposed to 125 Hz compared to bilateral vibration with the left hand exposed to 125 Hz and the right hand exposed to 31.5 Hz, in any finger, at any acceleration ($p>0.05$).

Comparing unilateral and bilateral vibration exposure

In general, there was no significant difference in FBF in any finger between unilateral and bilateral vibration at 31.5 or 125 Hz at 5.5, 11 and 22 ms^{-2} r.m.s. ($p>0.05$). However, with 31.5 Hz vibration at 22 ms^{-2} r.m.s. there was a greater reduction in FBF in the left and right middle and little fingers during bilateral vibration than during unilateral vibration ($p<0.05$).

8.3.4 Finger blood flow during the 'post-exposure application of force'

Unilateral vibration

After unilateral vibration, during the application of force in the 'post-vibration' push period, there were no significant differences within the five finger blood flow measurements in any finger ($p > 0.05$; Friedman).

Compared to during the pre-exposure period and the 'pre-exposure application of force' period finger blood flow in all fingers was significantly reduced in the post-exposure application of force period after unilateral vibration, ($p < 0.05$; Wilcoxon), except in the left little finger, where FBF was similar during the pre-exposure and the post-exposure application of force period after vibration at 31.5 Hz ($p=0.386$).

The end of vibration at 31.5 Hz and 125 Hz generally did not significantly change FBF in the middle or little fingers compared to FBF during exposure vibration at any magnitude ($p>0.1$). The exceptions were FBF in the right and left little fingers after 125 Hz vibration at 22 ms^{-2} r.m.s. ($p<0.05$) and FBF in the right middle ($p=0.053$) and both little fingers ($p<0.05$) after 125 Hz vibration at 11 ms^{-2} r.m.s.

During the 'post-exposure application of force' period following unilateral vibration, there was no significant difference in FBF between the exposed left middle finger and the unexposed right middle finger, or between the exposed left little finger and the unexposed right little finger ($p > 0.1$).

There was no significant difference in FBF in any finger between the 'post-exposure application of force' period following unilateral vibration at 31.5 Hz and unilateral vibration at 125 Hz ($p>0.1$), except in the left middle finger ($p=0.047$).

Bilateral vibration

After exposure to bilateral vibration, during 'post-exposure application of force', there were no significant differences within the five FBF measurements in any finger (p >0.1; Friedman), except after 31.5 Hz in the left middle finger (p=0.046).

During post-exposure application of force, the FBF in all fingers was significantly lower than during the pre-exposure period and during pre-exposure application of force (p <0.05).

During post-exposure application of force, the FBF in the middle and little fingers did not differ from the FBF during exposure to vibration at 5.5, 11, or 22 ms^{-2} r.m.s. (p > 0.1), except for 5.5 ms^{-2} r.m.s. at 125 Hz where there was a reduction in blood flow in the left middle finger compared to during vibration (p=0.015).

During post-exposure application of force following bilateral vibration, there were no significant differences in FBF between the left and right middle fingers, or between the left and right little fingers, (p > 0.1).

In all four fingers there were no significant differences in FBF after bilateral vibration at 31.5 Hz and after bilateral vibration at 125 Hz during the post-exposure application of force period (p>0.1).

During 'post-exposure application of force', there was no significant difference in FBF between bilateral vibration after both hands had been exposed to 31.5 Hz and bilateral vibration after the left hand was exposed to 125 Hz and the right hand was exposed to 31.5 Hz, in any finger (p>0.1). Similarly, there was no significant difference in FBF between bilateral vibration with both hands after exposure to 125 Hz compared to bilateral vibration after the left hand was exposed to 125 Hz and the right hand was exposed to 31.5 Hz, in any finger, at any vibration magnitude (p>0.1).

Comparing unilateral and bilateral vibration

In all four fingers there was no significant difference between FBF after unilateral vibration at 31.5 Hz and FBF after bilateral vibration at 31.5 Hz, in the 'post-exposure application of force' period (p> 0.05; Wilcoxon) except in the left middle finger (p=0.022; Wilcoxon). Similarly, there was no significant difference between FBF after unilateral vibration at 125 Hz and FBF after bilateral vibration at 125 Hz, for any finger (p >0.1; Wilcoxon).

8.3.5 Finger blood flow during the 'recovery period'

Unilateral vibration

During the recovery period after the removal of force following unilateral exposure to 125 Hz vibration, there were no significant differences within the 15 finger blood flow measurements

in any finger ($p > 0.1$; Friedman). After the removal of force following unilateral exposure to 31.5 Hz vibration, there were significant differences within the 15 finger blood flow measurements in all fingers ($p < 0.05$; Friedman), except in the left little finger (p=0.105).

Compared to the pre-exposure period and during the pre-exposure application of force period, the FBF in all fingers during the recovery period after vibration at 31.5 and 125 Hz was significantly reduced ($p< 0.05$; Wilcoxon).

Compared to during vibration exposure of 5.5 ms^{-2} r.m.s. at 31.5 Hz, the FBF in the right middle and little fingers during recovery was significantly reduced ($p <0.05$). However, in the left middle finger or in the left little finger there was no significant difference in FBF between the recovery period and during exposure to vibration at 5.5 ms^{-2} r.m.s. (left middle p=0.059) (left little p=0.139). Compared to during vibration exposure of 11 and 22 ms^{-2} r.m.s., there was no change in FBF during the recovery period in any finger ($p>0.1$).

Compared to during the 'post-exposure application of force' period, during recovery after exposure to 31.5 Hz unilateral vibration, the FBF in the right and left middle fingers was significantly reduced ($p < 0.01$), but there was no significant change in FBF in the little fingers ($p >0.1$).

During recovery, after exposure to 125 Hz unilateral vibration, the FBF in all fingers was not significantly different from the FBF during exposure to vibration at 5.5, 11 or 22 ms^{-2} r.m.s. ($p>0.1$). The exception was the FBF in the right middle finger which was significantly decreased during the recovery period, compared to the FBF during exposure to vibration at 5.5 ms^{-2} r.m.s. (p=0.047).

During recovery after exposure to 125 Hz unilateral vibration, the FBF in the right middle finger and the left little finger was significantly lower than during the 'post-exposure application of force' period ($p < 0.01$), but there was no significant change in FBF in the left middle finger and right little finger ($p > 0.1$).

During recovery after unilateral vibration of the right hand to either 31.5 or 125 Hz and the application of a push force to both hands, there was no significant difference in FBF between the middle fingers, or between the little fingers ($p > 0.1$), except for a significant difference between the little fingers after exposure to 125 Hz (p=0.028).

For all fingers, there was no significant difference between FBF during the 'recovery' period following unilateral vibration at 31.5 Hz and FBF during the 'recovery' period following unilateral vibration at 125 Hz ($p > 0.1$; Wilcoxon).

Bilateral vibration

During the recovery period after exposure to 31.5 Hz bilateral vibration, there were no significant differences within the 15 finger blood flow measurements in any finger ($p > 0.1$; Friedman). During recovery after exposure to 125 Hz bilateral vibration, there was significant variation in FBF during the recovery period in the middle fingers ($p< 0.05$) but no significant difference over the 15 measurements in the little fingers ($p>0.05$).

During recovery after exposure to both sessions of bilateral vibration, the FBF in all fingers was significantly lower than during the pre-exposure period and during the 'pre-exposure application of force' period ($p < 0.05$; Wilcoxon). The exception was FBF following bilateral vibration at 31.5 Hz when there was no significant difference between FBF during the pre-exposure application of force period and the recovery in the right little finger ($p=0.594$) and the left little finger ($p=0.767$), and following bilateral vibration at different frequencies in the left little finger ($p=0.093$).

During recovery following bilateral vibration at 31.5 and 125 Hz, there was no significant difference in FBF in any finger compared to the FBF during exposure to vibration at 11 ms^{-2} r.m.s. and 22 ms^{-2} r.m.s. ($p>0.1$). The FBF in all fingers was reduced during recovery compared to the finger blood flow during exposure to vibration at 5.5 ms^{-2} r.m.s. ($p < 0.05$).

During recovery after exposure to both sessions of bilateral vibration, there was no difference in FBF in any finger between the 'post-exposure application of force' period and the recovery period ($p >0.05$).

There was no significant difference between FBF in any fingers during the 'recovery' period following bilateral vibration at 31.5 Hz and the FBF during the 'recovery' period following bilateral vibration at 125 Hz ($p > 0.05$; Wilcoxon).

There was no significant difference in FBF between the left middle finger and the right middle finger, nor between the left and right little fingers, following bilateral vibration at 31.5 or 125 Hz, or following bilateral vibration at different frequencies ($p>0.1$), except after bilateral vibration at 125 Hz in the middle fingers ($p=0.024$).

Comparing unilateral and bilateral

For all fingers, there was no significant difference between FBF during the 'recovery' period following unilateral vibration and FBF during the 'recovery' period following bilateral vibration ($p>0.1$; Wilcoxon).

8.4 DISCUSSION

8.4.1 Push force

In this study, a push force of 2 N applied by the palms tended to reduce finger blood flow, although the reduction was not statistically significant.

Previous studies have found that the application of a 2-N push force to the medial phalanx of a finger reduces finger blood flow (Chapters 5 and 6; Bovenzi *et al.*, 2006). A 2-N push force applied to the palm did not alter finger blood flow in the exposed hand (Chapters 6 and 7).

With a 2-N force applied at the palm, compression of the vascular system so as to reduce the circulation to the finger is less likely. However, in this study the application of push force to both palms was a sufficient trigger to affect blood flow, although the reduction was not statistically significant. There may be a cumulative effect of push force on finger blood flow.

A control condition consisting of exposure of two hands to a 2-N push force applied to the palms would have provided a clear picture of the dependence of finger blood flow on push force during and after exposure.

8.4.2 During vibration

In general, during vibration, this study found no significant difference in FBF in any finger between unilateral and bilateral vibration at 31.5 or 125 Hz. The exception was a stronger reduction in flow at 31.5 Hz at 22 ms^{-2} r.m.s. during bilateral vibration than during unilateral vibration. The similar vasoconstriction during unilateral and bilateral vibration suggests that vibration of two hands does not double the dose of vibration at the magnitudes investigated.

With unilateral and bilateral vibration, the vibration frequency affected the strength of vasoconstriction. With an equal vibration velocity of 0.028 ms^{-1} at both frequencies (5.5 ms^{-2} r.m.s. at 31.5 Hz and 22 ms^{-2} r.m.s. at 125 Hz), finger blood flow was significantly reduced during vibration at 125 Hz compared to vibration at 31.5 Hz. Chapters 6 and 7 reported a stronger reduction in finger blood flow during vibration at 125 Hz than during vibration at 31.5 Hz with similar ranges of vibration velocity at both frequencies.

In this study, during unilateral and bilateral vibration with equal acceleration magnitudes (5.5, 11, and 22 ms^{-2} r.m.s.) at 31.5 Hz and 125 Hz, there was no difference in the reduction in blood flow between the frequencies.

During vibration of the right hand at 31.5 or 125 Hz, this study did not find a significantly stronger reduction in blood flow as the vibration magnitude increased. However, the trend could be seen (Table 8-2). The general dependence of finger blood flow on vibration

magnitude in this study supports the findings in Chapters 5 to 7 where a strong dependence of FBF on vibration magnitude was found between 0 to 15 ms^{-2} r.m.s. (weighted).

During vibration of two hands, finger blood flow was significantly dependent on vibration magnitude. Bilateral vibration at 125 Hz with a vibration magnitude of 11 ms^{-2} r.m.s. reduced finger blood flow compared to vibration of 5.5 ms^{-2} r.m.s. When vibrating two hands at 31.5 Hz, vibration with 22 ms^{-2} r.m.s. resulted in a greater reduction in finger blood flow than vibration with a vibration magnitude of 11 ms^{-2} r.m.s. Chapters 5 to 8 found increasing vibration magnitude reduced finger blood flow. Vibration to one hand at low magnitudes may not have provoked a strong enough stimulus to be distinguishable from vasoconstriction resulting from a push force to two hands. Vibration of two hands may have provided a sufficient stimulus for blood flow to be dependent on the vibration magnitude.

The frequency-weighted magnitudes in this study (0.7, 1.4 and 2.8 ms^{-2} r.m.s.) at 125 Hz are similar to the lower magnitudes of the linearly increasing acceleration (0 to 15 ms^{-2} r.m.s. weighted) in Chapters 5 to 7. In Chapter 7 vibration and force applied to one hand at 0.5 and 1.0 ms^{-2} r.m.s. (weighted) at 125 Hz did not change finger blood flow compared to finger blood flow during the 'pre-exposure application of force' period. In this study, vibration of one hand and force applied to two hands at 0.7, 1.4 and 2.8 ms^{-2} r.m.s at 125 Hz reduced finger blood compared to finger blood flow during push force. The greater reduction in FBF in this chapter may have arisen because of reductions in FBF caused by force to two hands.

During unilateral vibration the finger blood flow was similar in the fingers of the exposed hand and the unexposed hand. The equal reduction in flow in the exposed and unexposed hands at 31.5 and 125 Hz gives confidence to the findings of Chapters 6 and 7. The results in Chapters 6 to 8 are consistent with the vascular response to vibration being centrally mediated.

8.4.3 After vibration

In this study there was no difference between finger blood flow after unilateral vibration and finger blood flow after bilateral vibration.

Immediately after the end of unilateral and bilateral vibration, this study found a continued vasoconstriction compared to finger blood flow before exposure to vibration and push force. The findings in this study are consistent with the findings in Chapters 6 and 7 where vibration of the right palm at 31.5 and 125 Hz produced a continued reduction in blood flow in both hands after vibration had ceased.

A large increase in blood flow immediately after the end of vibration has been seen in some experiments where push force has affected blood flow (Chapter 5; Chapter 6). With the

simultaneous end of push force and vibration, a brief return to pre-exposure finger blood flow has been reported in an exposed hand (Bovenzi *et al.*, 1998, 1999, 2000, 2001). The increase in blood flow on cessation of vibration in this study was small, consistent with the push force to both hands causing only a small reduction in blood flow.

Strong vasoconstriction occurred during the recovery period 5 minutes after the end of vibration exposure. There was no difference in vasoconstriction during the 'recovery' period following unilateral and bilateral vibration exposure at 31.5 and 125 Hz. In Chapters 6 and 7 with equal velocity the vasoconstriction was stronger after unilateral exposure to 125 Hz than after unilateral exposure to 31.5 Hz. In this study the velocity (and unweighted acceleration magnitudes) was greater at 31.5 Hz than during exposure at 125 Hz.

In this study there was a large variation over the 15 measurements of FBF during the recovery period after unilateral vibration at 31.5 Hz. A large variation in finger blood flow during the recovery did not occur following vibration at 31.5 Hz in the studies reported in the previous chapters, however at 31.5 Hz finger blood flow returned to pre-exposure levels more rapidly than at other frequencies. The large variation over the 15 measurements of finger blood flow may be the return of finger blood flow to pre-exposure levels as reported in chapters 6 and 7.

Bovenzi *et al.* (1998) found that the reduction in blood flow after vibration was dependent on the vibration exposure duration and Bovenzi *et al* (2001) found that the reduction in flow after vibration was dependent on the vibration frequency. The difference between the unilateral and bilateral vibration conditions (e.g. at 125 Hz) was the vibration of a second hand during bilateral vibration but this did not affect the vasoconstriction following vibration exposure. Vibration to two hands did not therefore activate a stronger vasoactive response than vibration to one hand.

Following unilateral and bilateral vibration exposure, there was no significant difference in blood flow between the two hands. The similarity in blood flow between the two hands supports the hypothesis that the reduction in blood flow after vibration is centrally mediated.

8.5 CONCLUSION

At most of the vibration magnitudes investigated, vibration and push force applied to two hands did not reduce finger blood flow compared to the same vibration and push force applied to only one hand. Similarly, following the cessation of vibration applied to one or both hands, there was no difference in the finger blood flow. The results of the experiment are consistent with vasoconstriction during and after unilateral and bilateral vibration being activated by a centrally mediated mechanism. Push force may affect finger blood flow.

CHAPTER 9

DISCUSSION

In the previous chapters there was a discussion comparing the findings of each experiment with the results reported from previous studies. This chapter presents a summary of the main findings from each chapter and discusses the hypotheses tested in this thesis.

The hypotheses tested in this research are:

a. Previous observations of the effect of vibration on finger blood flow have been confounded by the effect of push force

b. Increasing the magnitude of vibration will reduce the finger blood flow

c. The reduction in finger blood flow is dependent on the frequency of the vibration

d. Vibration will produce the same reduction in finger blood flow in exposed and unexposed hands

9.1 Previous observations of the effect of vibration on finger blood flow have been confounded by the effect of push force

An objective of this thesis was to determine whether push force affected finger blood flow. Previous observations of the dependence of FBF on vibration may have been confounded by the effect of push force during and after vibration exposure.

The strength of the force and the locations of the applied force in some of the present experiments were chosen so that a force and a location could be identified that would not confound the acute effects of vibration on finger blood flow.

9.1.1 During push force

In Chapters 5 and 6, a 2-N push force applied to the finger significantly reduced blood flow in the exposed finger for the duration of the application of force, while no change in FBF was found in the unexposed hand. A reduction in FBF in the exposed hand is consistent with Bovenzi *et al.* (2006) who found reduced blood flow in the exposed finger during a 5-minute exposure to vibration using the same contact

conditions and force as in Chapter 5. Bovenzi *et al.* (2006) reported that the fingers of the unexposed hand were not affected by force.

In Chapters 5 and 6 it was concluded that the application of a 2-N force to the finger caused a reduction in blood flow large enough to confound the measurement of finger blood flow in the exposed hand during vibration. Previous studies have applied a force to the fingers. Bovenzi and Griffin (1997) and Bovenzi *et al.* (1995, 1998, 2000) reported that exposure to a static 10-N load applied to the fingers for 30 minutes did not cause significant vasoconstriction. It was deduced that force did not confound the effects of vibration on finger blood flow. However, the 10 N force was distributed over a large area and thereby exposed each phalanx to a lower pressure than the load in Chapters 5 and 6.

Bovenzi *et al.* (2004) used a similar force as Bovenzi and Griffin (1997) and Bovenzi *et al.* (1995, 1998, 2000) and found a 10 N force reduced finger blood flow in the exposed hand, while not changing FBF in the unexposed hand.

Bovenzi *et al.* (2006) state that a reduction in finger blood flow when push force is applied to the phalanx of a finger is likely to be due to mechanical compression of the digital arteries. Compression of the vasculature may be blocking the blood flow. In addition, a physiological response to the compression of the vasculature could be occurring in the digit exposed to force.

In order to investigate the effect of vibration on finger blood flow without the confounding influence of compression, push force and vibration had to be applied to an area of the hand that did not block finger blood flow.

In Chapters 6 and 7 the application of a force of 2 N to the palm did not reduce finger blood flow and therefore would not confound the measurement of finger blood flow during vibration. The findings in Chapters 6 and 7 are consistent with the findings of Griffin *et al.* (2006) who observed that the application of a 5 N force to the palm did not affect finger blood flow. A stronger force of 20 N applied to the palm resulted in a reduction in finger blood flow in the exposed and unexposed hands. Griffin *et al.* (2006) report that vibration applied with a 20 N push force caused a greater reduction in blood flow than exposure with the same vibration characteristics and a 5 N push force.

A long exposure to a force may affect finger blood flow. Griffin *et al.* (2006) report that a 5 N force applied to the palm for 15 minutes significantly reduced blood flow in

the middle finger of the exposed hand but not in the unexposed hand. The exposure durations in this series of experiments were longer that those of Griffin *et al.* (2006). The control conditions in Chapters 5 and 6 showed that blood flow did not progressively reduce over 22 or 30-minute durations of exposure to push force. In Chapter 7 a variation in finger blood flow was recorded over the 30-minute application of force to the finger in the control condition. Finger blood flow was seen to increase and decrease over the exposure duration, rather than gradually decreasing over time.

In Chapter 8, the application of a 2-N push force to both palms tended to reduce finger blood flow but the reduction was not statistically significant. There may be a cumulative effect of push force because Chapters 6 and 7 found that the application of a 2-N push force to one palm did not progressively decrease finger blood flow. The force to both palms may have confounded the measurement of finger blood flow during vibration exposure. A no-vibration control condition of push force to both palms, in Chapter 8, would have identified the effect on finger blood flow of a 2 N push force to both palms.

Bovenzi *et al.* (2006) found that with the subject in a resting position the reduction in finger blood flow in the exposed hand with no push force applied was similar to the reduction in finger blood flow during a 2-N push force to the finger. The reduction was attributed to 'a change in the height of the finger relative to the heart during the lateral movement needed to place the finger on the wooden platform or, slight compression on the digital arteries when the middle right finger rested on the wooden platform' (Bovenzi *et al.*, 2006).

In Chapter 8 to minimise any movement artefacts the two hands were supported at the same height relative to the heart throughout the experimental session. In particular, the exposed hands were kept at the same height relative to the heart during the lateral movement of the hands from the hand supports to the wooden contactors attached to the vibrators.

Other laboratory studies have reported adverse acute effects of force on finger circulation. Hartung *et al.* (1993) report a dependence of skin temperature on grip force that was accounted for by mechanical compression of the blood vessels when using a gripping posture. Similarly, when using a gripping posture, Scheffer and Dupuis (1989) report that the static load proved to have a strong influence on the reduction of skin temperature. It is possible that the reduction in skin temperature

experienced by Hartung *et al.*, (1993) and Scheffer and Dupuis (1989) was due to compression of the vasulature or a locally mediated vasoconstriction because of the gripping posture adopted by subjects and the application of high grip and push forces.

This thesis concludes that a push force can reduce finger blood flow with the reduction being dependent on the force and the location of the applied force. Previous observations of the dependence of finger blood flow on vibration may have been confounded by the effect of push force during and after vibration exposure. The strength and location of the push force were found to influence finger blood flow.

9.1.2 After push force

The effect on digital blood flow of removing a push force was investigated in Chapters 5 and 6. The removal of a 2-N push force from the finger caused an increase in blood flow in the exposed digit, with FBF returning to the FBF during pre-exposure application of force, although removal of force had no effect on FBF in the digit of the unexposed left hand. It is suggested that the removal of the force from the finger simply relieved compression of the arteries, causing an increase in blood flow in the exposed digit (Bovenzi *et al.* 2006).

Bovenzi and Griffin (1997) and Bovenzi *et al.* (1998, 2000) found the removal of a static 10-N push force applied by the right hand did not significantly change finger blood flow. As the application of force in Bovenzi and Griffin (1997) and Bovenzi *et al.* (1998, 2000) was found not to affect finger blood flow, it is reasonable that the removal of force did not affect finger blood flow. The force per phalanx (i.e. the pressure) may have been sufficiently low to allow blood flow during exposure.

In Chapters 6 and 7 the removal of a push force from the palm did not change finger blood flow in either hand. A 2-N push force to the palm does not seem to have compressed the vasculature in the palm or triggered a physiological response to the applied force, hence the absence of an after-effect with the removal of force. This finding gives confidence that the assumption that a 2-N push force to the palm did not affect the vascular response after vibration exposure.

Griffin *et al.*, (2006) reported that the removal of forces greater than 2 N (i.e. 5 N or 20 N) from the palm cause a large increase in blood flow in the exposed digits. The greater push forces in the Griffin *et al.* (2006) study than in Chapters 6 and 7 appears

to have been sufficient to compress the vasculature in the palm or trigger a physiological response that was released when force was removed.

In Chapter 8, the removal of 2-N push force from both palms 10 minutes after vibration exposure resulted in a increase in blood flow in the fingers of both hands compared to finger blood flow during exposure to force and vibration. The increase in blood flow with the removal of push force may be due in part to the exposure of both hands to push force. A no-vibration control condition of push force to both palms, in Chapter 8, would have identified the effect on finger blood flow of removing a 2-N push force from both palms.

Previous laboratory experiments have investigated the dependence of finger blood flow on the simultaneous removal of force and vibration from the hand. With the cessation of vibration and a 10-N push force applied to the fingers, Bovenzi and Griffin (1997) and Bovenzi *et al.* (1998, 1999, 2000, 2001) reported an immediate vasodilation in an exposed digit compared to pre-exposure FBF. In a few studies, a significant vasodilation been reported in the unexposed contralateral hand following the simultaneous removal of both force and vibration (Bovenzi and Griffin, 1997; Bovenzi *et al.*, 1995, 1998, 2000). The exceptions are vasodilation in the unexposed hand following vibration of 62 ms^{-2} r.m.s. at 125 Hz (Bovenzi *et al.*, 1999) and following vibration at 125 Hz of 44 ms^{-2} r.m.s. for 30 minutes and vibration of 88 ms^{-2} r.m.s. for 7.5 minutes (Bovenzi *et al.*, 2001). The vasodilation in the exposed hand may be due to the relieving of compression of the digital vasculature in the exposed digits.

This thesis concludes that the removal of push force can relieve the reduction in finger blood flow caused by the force and that the effect is dependent on the location of the force on the hand. Some of the previous observations of the dependence of finger blood flow on vibration after vibration has ceased have been confounded by the effect of push force. The strength and location of push force have been found to influence finger blood flow.

9.2 Increasing vibration magnitude will reduce the finger blood flow

A key objective of this thesis was, after eliminating the influence of push force, to determine whether the reduction in blood flow during vibration was approximately proportional to the magnitude of the vibration.

The results in Chapter 5 are consistent with the findings of previous investigations. Finger blood flow in the exposed hand was dependent on the vibration magnitude between 0 to 11 ms^{-2} r.m.s. (frequency-weighted) at 125 Hz. Bovenzi *et al.* (1999) found finger blood flow in the exposed and unexposed digits was inversely proportional to vibration magnitude in the range of 0.69 to 7.75 ms^{-2} r.m.s. (weighted) at 125 Hz.

In Chapters 6 and 7 exposures to magnitudes of 0 to 15 ms^{-2} r.m.s. (frequency-weighted) at frequencies between 16 and 315 Hz (0 to 11 ms^{-2} r.m.s. at 315 Hz) caused a reduction in the blood flow in the exposed and unexposed fingers. At all frequencies the reduction was dependent on the magnitude of the vibration input.

Bovenzi *et al.* (1999) vibrated a hand at 125 Hz with varying acceleration magnitudes. The reductions in finger blood flow in Chapter 7 at 125 Hz were consistent with the reductions in finger blood flow in the unexposed hand at the same frequency-weighted acceleration magnitudes in the study by Bovenzi *et al.* (1999). Welsh (1980) reported a dwindling blood flow as the magnitude of the vibration displacement at 80 Hz increased from 0.125 to 1.0 mm. At a frequency of 60 Hz, Luo *et al.* (2000) found that 31.6 ms^{-2} r.m.s. caused a stronger vasoconstriction than 3.16 ms^{-2} r.m.s.

In Chapters 4 to 7 by using linearly increasing acceleration it was possible to see that finger blood flow reduced in proportion to vibration acceleration within the range of magnitudes investigated. Comparing the results of the experiments reported in Chapters 5 to 8 gives confidence that during vibration exposure finger blood flow is dependent on the vibration magnitude and reinforces the hypothesis that push force to both hands may have conflicted with the effect of magnitude. Previous studies have not so precisely quantified the relationship between finger blood flow and acceleration magnitude.

In contrast to previous experiments using unilateral exposure to vibration, finger blood flow during unilateral vibration in Chapter 8 did not show a dependence on vibration magnitude in the range 5.5 to 22 ms^{-2} r.m.s. (unweighted). At a frequency of 125 Hz, the frequency-weighted magnitudes in Chapter 8 (0.7 to 2.82 ms^{-2} r.m.s.) are similar to the low magnitudes in Chapter 7 (0 to 15 ms^{-2} r.m.s. weighted). However, in Chapter 7 during unilateral vibration at 125 Hz with a magnitude of 0.5 and 1.0 ms^{-2} r.m.s., finger blood flow was not significantly reduced compared to during pre-exposure application of force. Whereas, in Chapter 8, vasoconstriction occurred at all

vibration magnitudes of unilateral vibration (0.7 to 2.82 ms^{-2} r.m.s.), compared to finger blood flow during the pre-exposure application of force period. The application of force to both palms may have contributed to the vasoconstriction in Chapter 8 since no vasoconstriction occurred at similar magnitudes in Chapter 7 when one hand was exposed to force.

In Chapter 8 a dependence of finger blood flow on vibration magnitude during vibration of two hands was evident. Vibration of two hands at 11 ms^{-2} r.m.s. (5.5 ms^{-2} r.m.s. frequency-weighted) caused a stronger vasoconstriction than vibration at 5.5 ms^{-2} r.m.s. (2.75 ms^{-2} r.m.s. frequency-weighted) at 31.5 Hz. Increasing the vibration magnitude from 11 ms^{-2} r.m.s. to 22 ms^{-2} r.m.s. did not reduce finger blood flow. It was expected from Chapters 6 and 7 that blood flow would gradually reduce with increasing vibration magnitude at 31.5 Hz. In Chapter 8, a vibration acceleration of 22 ms^{-2} r.m.s. (2.75 ms^{-2} r.m.s. frequency-weighted) reduced finger blood flow more than vibration of 11 ms^{-2} r.m.s. (1.41 ms^{-2} r.m.s. frequency-weighted) at 125 Hz. It is not clear why there was not a greater reduction in finger blood flow at 11 ms^{-2} r.m.s. compared to finger blood flow at 5.5 ms^{-2} r.m.s.

In Chapter 8 vibration of two hands at each magnitude caused the same reduction in finger blood flow as vibration of one hand. Perhaps there is a saturation point at each magnitude, which means that even if the vibration stimulus is doubled (e.g. exposure to two hands) there is no further increase in vasoconstriction.

In conclusion, by using a linearly increasing (i.e. ramped) magnitude of vibration in Chapters 4 to 7 it was possible to identify that finger blood flow appears to be inversely proportional to vibration acceleration magnitude. The research reported in this thesis has provided a greater understanding of the characteristics of the vascular response to vibration magnitude.

9.3 Reductions in finger blood flow depend on the frequency of the vibration

Over the range of frequencies investigated, this thesis reports that higher frequencies of hand-transmitted vibration caused a stronger reduction in blood flow than lower frequencies both during and after vibration exposure.

9.3.1 During vibration exposure

In Chapter 7 the principal effects of vibration frequency are presented. Acute exposure to vibration frequencies in the range of 16 to 315 Hz with equal frequency-weighted accelerations of 0 to 15 ms^{-2} r.m.s. (0 to 11ms^{-2} r.m.s. at 31.5 Hz) caused

reductions in finger blood flow compared to pre-exposure finger blood flow (Chapter 7). The reduction in finger blood flow was greater at higher frequencies than at lower frequencies. The vascular responses in Chapter 7 are compatible with the vascular responses to frequency from one subject presented in the pilot study in Chapter 6. In Chapter 6, vibration at higher frequencies induced a stronger vasoconstriction than vibration at lower frequencies.

Previous experimental studies have investigated the acute effects of the frequency of vibration on finger blood flow with either the same acceleration, the same velocity, or the same displacement at each frequency. With the same acceleration magnitudes of 10 and 50 ms^{-2} r.m.s., Furuta *et al.* (1991) found stronger vasoconstriction at frequencies from 31.5 to 63 and from 250 to 500 Hz than at 125 Hz. However, Bovenzi *et al.* (2006) compared the effect of vibration frequency and found no difference in the degree of vasoconstriction after vibration at 31.5 and 125 Hz when using an acceleration of 16 ms^{-2} r.m.s. With the same displacement at all frequencies, Welsh (1980) reported that vibration frequencies in the range 80 to 125 Hz provoked a marked vasoconstriction compared to lower and higher frequencies.

In Chapters 6 and 7 the acute effects of the frequency of vibration on finger blood flow with the same range of velocity (0 - 11 ms^{-1} r.m.s.) at each frequency were examined. With the same velocity, Bovenzi *et al.* (2000) reported that, as vibration frequency increased, the FBF in the unexposed finger reduced, within the frequency range 31.5 to 250 Hz. The vascular dependence on vibration frequency in Bovenzi *et al.* (2000) gives confidence to the relationship between frequency and finger blood flow found in Chapters 6 and 7.

Aside from the differences in vibration stimuli, the location of the vibration on the hand may influence the vascular dependence on vibration frequency. In previous experimental studies the location of vibration to the hand has been varied. Furuta *et al.* (1991) applied vibration to the palm. Bovenzi *et al.* (2000) positioned all fingers to be in contact with the vibrating plate and reported that vasoconstriction in the exposed finger did not show the same frequency dependence as a digit on the unexposed hand. Bovenzi *et al.* (2000) found that vasoconstriction was less strong in the exposed hand at 16 Hz than between 31.5 and 250 Hz.

In Chapter 6 the effects of vibration frequency (16 to 250 Hz and with vibration magnitudes from 0 to 15 ms^{-2} r.m.s) on vasoconstriction at two different contact locations were examined. A dependence of finger blood flow on vibration frequency

was evident when vibration was applied to the palm or the hand. However, the lower frequencies showed a stronger response with finger contact than with palm contact. There was similar vasoconstriction with finger and palm contact at higher frequencies in Chapter 6. The findings of Chapter 6 provide some explanation for the difference in vascular response between the exposed and unexposed hands reported by Bovenzi *et al.* (2000) and the dependence of finger blood flow on vibration frequency reported in Chapter 7.

In Chapter 8 the application of vibration and push force to two palms did not change the dependence of finger blood flow on vibration frequency. During vibration of two hands (Chapter 8) with a velocity of 5.5 ms^{-1} r.m.s. vasoconstriction was stronger at 125 Hz vibration (22 ms^{-2} r.m.s. unweighted) than at 31.5 Hz vibration (5.5 ms^{-2} r.m.s. unweighted). The reduction in blood flow during bilateral vibration at 125 Hz to the left hand and 31.5 Hz to the right hand was not significantly different from the reduction in finger blood flow during vibration applied to both hands at 31.5 Hz or 125 Hz. Chapter 8 indicates that the vascular response during vibration is dependent on the vibration frequency with constant velocity. Chapter 8 also indicates that the location of push force can confound the dependence of finger blood flow on vibration frequency.

In Chapter 7 the dependence of finger blood flow on frequency-weighted vibration acceleration was compared. With 250 and 315 Hz, very low magnitudes of vibration (0.5 and 1.0 ms^{-2} r.m.s. frequency-weighted) reduced finger blood flow compared to pre-exposure blood flow (Chapter 7). However, low acceleration magnitudes from 16 to 125 Hz did not significantly reduce blood flow compared to blood flow during push force to the finger. The immediate vasoconstriction during vibration of very low frequency-weighted acceleration magnitudes suggests that the mechanism triggering vasoconstriction is particularly sensitive at higher frequencies.

Previous studies have attributed sensitivity at higher frequencies, particularly at 125 Hz, to the Pacinian mechanoreceptors (Bovenzi and Griffin, 1997). The particular sensitivity of finger blood flow to vibration at 125 Hz has been demonstrated in Chapters 5 to 7 of this thesis and in previous studies (Bovenzi and Griffin, 1997; Bovenzi *et al.*, 1998, 2000, 2001, 2006; Griffin *et al.*, 2006).

This thesis reports that during acute vibration exposure with the same range of velocities higher frequencies of hand-transmitted vibration caused a stronger reduction in blood flow than lower vibration frequencies.

9.3.2 After vibration exposure

After the end of exposure to vibration at 16 to 315 Hz, finger blood flow was reduced compared to finger blood flow before the application of vibration and push force.

In Chapter 7 the principal after-effects of vibration at different frequencies are presented. In Chapter 7, with the same velocity at each frequency, the strength of the vasoconstriction was dependent on the frequency of the vibration within the range 16 to 315 Hz. A stronger reduction in finger blood flow was reported after exposure at 125 Hz than after exposure at higher or lower frequencies. With the same velocity of vibration at each frequency, a similar dependence of finger blood flow on the vibration frequency was found in the pilot study in Chapter 6 as in Chapter 7. A greater reduction in blood flow was found at the higher frequencies of 125 and 250 Hz than at the lower frequencies, such as 16 and 31.5 Hz.

Bovenzi *et al.* (2000) found that following a post-vibration vasodilation vibration frequencies of 125 and 250 Hz induced stronger vasoconstriction than vibration of 16 Hz or no-vibration (a control condition). Bovenzi *et al.* (2000) used the same velocity of 5.5 ms^{-1} r.m.s. at all frequencies. With a velocity of 2 or 8 ms^{-1} r.m.s., Bovenzi *et al.* (2006) reported a stronger vasoconstriction after vibration at 125 Hz than after vibration at 31.5 Hz. The findings of Bovenzi and Griffin (2000) seem consistent with the results in Chapters 6 and 7 where the same velocity was used to investigate the dependence of finger blood flow on vibration frequency.

In Chapter 8 with the same acceleration, vibration of two hands at 31.5 Hz produced the same vasoconstriction after exposure as the vibration of two hands at 125 Hz. The same reduction in flow was found following exposure of both hands to either 31.5 or 125 Hz as following exposure of the left hand to 125 Hz and the right hand to 31.5 Hz. Other studies using the same acceleration have reported a dependence of finger blood flow after vibration with varying frequencies and at constant acceleration. Bovenzi and Griffin (1997) found a stronger reduction in blood flow 20 to 40 minutes after vibration to one hand at 125 Hz with 22 ms^{-2} r.m.s. (unweighted), than after vibration at 31.5 Hz with 22 ms^{-2} r.m.s. (unweighted). Bovenzi and Griffin (1997) exposed all digits of one hand to vibration, which may account for the vascular response reported. With constant acceleration of 50 ms^{-2} r.m.s., Nohara *et al.* (1986) found a stronger vasoconstriction following vibration at 60 and 480 Hz than following vibration at 30, 120, 240 and 960 Hz. Nohara *et al.* (1986) employed a clasped hand posture to apply vibration to the whole hand. In Chapter 8 there was no difference in

the strength of vasoconstriction measured between frequencies following vibration with constant acceleration. The studies that reported a dependency of finger blood flow on vibration frequency following constant vibration acceleration exposed large areas of the hand, or the complete hand, to vibration. The contact area and location have been shown to confound the measurement of the effects of vibration on finger blood flow.

Welsh (1980) reported that with the same vibration displacement at all frequencies that blood flow recovered within two minutes after ceasing vibration of the finger at frequencies of 40, 80, 120, 160 or 200 Hz. It is possible that the simultaneous release of force and vibration from the finger provoked a brief recovery in the earlier studies.

Similar to Welsh (1980), Bovenzi *et al.* (2000) simultaneously released force and vibration from the finger and found an immediate vasodilation in the exposed digit. Both studies report that the vasodilation following vibration was independent of vibration frequency. Section 9.1.2 discusses the cause of the vasodilation in the exposed hand.

Current standards for hand-transmitted vibration assume that the vascular response during vibration is independent of the vibration frequency when the magnitude has a constant velocity at frequencies from 16 to 1000 Hz. Previous studies, and the findings of this thesis, show that the frequency-weighting in ISO 5349 (2001) is suspect and does not predict the vascular response to vibration frequency either during or after vibration exposure. It would seem that the vascular response could be more accurately predicted during and after vibration using a weighting based on similar sensitivity to the vibration acceleration over at least some of the frequencies studied here.

This thesis concludes that after vibration exposure with the same velocity at all frequencies, the higher frequencies of hand-transmitted vibration cause a stronger reduction in blood flow than lower frequencies. With the same acceleration at all frequencies, there was little or no difference in finger blood flow after vibration at varying frequencies.

9.4 Vibration produces the same reduction in finger blood flow on exposed and unexposed hands

9.4.1 During vibration exposure

Some previous studies found that vibration to one hand provoked a vasoconstriction in the exposed and unexposed hand (Furuta *et al.*, 1991; Bovenzi and Griffin, 1997; Bovenzi *et al.*, 1998, 1999, 2000, 2001, 2006; Griffin *et al.*, 2006). In accord with previous studies, this thesis found vasoconstriction in the unexposed left hand while the right hand was vibrated (Chapters 5 to 8).

In some studies, the vasoconstriction during vibration exposure has been significantly greater in the exposed hand than in the unexposed contralateral hand (Bovenzi and Griffin, 1997; Bovenzi *et al.*, 1998, 1999, 2000, 2001). With vibration applied to a finger in Chapter 5, there was a more pronounced reduction in finger blood flow on the exposed hand than on the unexposed hand. In Chapter 6, the stronger reduction in finger blood flow on the exposed hand was attributed to a confounding influence of push force to the finger (Section 9.1) as vibration of a palm produced an equal reduction in finger blood flow in the exposed and unexposed hands.

The findings in Chapter 7 are consistent with the findings in Chapter 6. Vibration applied to the palm produced an equal reduction in finger blood flow in an exposed and unexposed hand during vibration with accelerations of 0 to 15 ms^{-2} r.m.s. at 16 to 315 Hz. The frequency and magnitude of the vibration did not affect the equal response in both hands, within the ranges of vibration investigated.

In Chapter 8 an equal reduction in flow in both hands was reported during unilateral vibration of the right hand. Without the confounding influence of push force on finger blood flow, exposure of one hand to vibration caused an equal reduction in flow in the exposed hand and the unexposed contralateral hand during and after vibration exposure. The findings in Chapters 6 to 8 are consistent with the theory that vibration activates a centrally mediated vasoconstriction in both hands during vibration exposure (Egan *et al.*, 1996; Bovenzi and Griffin, 1997; Bovenzi *et al.*, 1998, 1999, 2000, 2001).

In Chapters 6 to 8 the equal reductions in finger blood flow during vibration exposure challenge the theory that the vasoconstriction in the exposed hand is the result of local vasoconstrictor agents in addition to a centrally mediated vasoconstriction (Bovenzi *et al.*, 1998, 1999, 2000, 2001).

In chapter 8 vibration applied to two hands or one hand caused the same reduction in finger blood flow during vibration exposure at 125 Hz and at 31.5 Hz with accelerations of 5.5, 11 and 22 ms^{-2} r.m.s. The exception was with 31.5 Hz at 22 ms^{-2} r.m.s. when the reduction in finger blood flow was greater during vibration of two hands, than during vibration of one hand. Had local vasoconstrictor agents been active in the exposed hand, the vasoconstriction in the unexposed hand during unilateral vibration would have been less than the blood flow in the same hand during bilateral vibration in Chapter 8.

The findings in this thesis are inconsistent with the vascular response reported in some previous studies. Furuta *et al.* (1991) applied vibration to the palm but still found a stronger response in the exposed hand than in the unexposed contralateral hand. Furuta *et al.* (1991) used a greater push force than was used in this thesis. The push force may have affected the digital blood flow as Griffin *et al.* (2006) identified that a push force greater than 5 N applied to the palm could affect the finger blood flow in the exposed hand during vibration exposure. A study by Welsh (1980) reported no change in blood flow in the unexposed contralateral left hand during vibration of the right hand at magnitudes between 0.05 to 0.5 mm (peak-to-peak displacement) at frequencies between 40 to 200 Hz for two minutes. Likewise, Bovenzi *et al.* (2004) report that there were no reductions in blood flow in the fingers on the unexposed hand during intermittent vibration at 125 Hz with an acceleration of 1.4 ms^{-2} r.m.s. The absence of vasoconstriction in the unexposed hand found by Bovenzi *et al.* (2004) was attributed to the low acceleration magnitudes of vibration.

The results in this thesis support the hypothesis that vibration activates a centrally mediated vasoconstriction in both exposed and unexposed hands during vibration exposure.

9.4.2 After vibration exposure

In Chapter 5, immediately after vibration of one finger (at 125 Hz from 0 to 11 ms^{-2} r.m.s.) there was a continued reduction in finger blood flow that was stronger in the exposed digit than in the unexposed digit. The difference in finger blood flow between the exposed and unexposed hands can be attributed to the push force on the exposed hand (Section 9.1). Similarly, during the recovery period the removal of push force from the finger caused vasodilation in the exposed hand but did not change finger blood flow in the unexposed hand. The findings in Chapter 5 are consistent with the findings of Bovenzi *et al.* (1998, 1999, 2000, 2001, 2006) who

found a different response in the exposed hand to the unexposed hand immediately following simultaneous cessation of vibration and force.

Vasodilation in the exposed hand following the simultaneous removal of vibration and force has been reported in previous studies (see Section 9.1.2). The effect of force on finger blood flow was eliminated in Chapters 6 and 7 with the result that the immediate after-effect of vibration was equal vasoconstriction in both hands and not vasodilation in the exposed hand as found in previous studies. The equal vasoconstriction in both hands lasted for the remaining ten minutes of the experimental session and was frequency-dependent between 16 and 315 Hz at magnitudes from 0 to 15 ms^{-2} r.m.s. (frequency-weighted) (see Section 9.3). The removal of push force from the exposed hand did not change the finger blood flow after vibration exposure.

Some previous studies have reported a reduction in finger blood flow in the exposed and unexposed hands fifteen minutes after the end of vibration exposure (Bovenzi and Griffin, 1997; Bovenzi *et al.*, 1998, 1999, 2000, 2001, 2006; Griffin *et al.*, 2006), with vasoconstriction stronger in the exposed hand than in the unexposed hand in some studies (Bovenzi *et al.*, 1998, 1999, 2004) but not in others (Bovenzi *et al.*, 2000, 2001). The findings of Chapters 6 and 7 complement the results of Bovenzi *et al.* (2000, 2001) who report equal reductions in blood flow in the exposed and unexposed hand 30-minutes after exposure to vibration between 16 to 250 Hz.

Although Bovenzi *et al.* (1998, 1999, 2004) report a stronger vasoconstriction in the exposed hand than in the unexposed hand after the cessation of vibration exposure, it is interesting that these three experiments were conducted at a frequency of 125 Hz. Similar contact conditions were used in other studies (Bovenzi *et al.*, 2000, 2001) with various frequencies and it was reported that the vascular system seemed most sensitive to vibration at 125 Hz. The application of force with vibration may provoke a particularly sensitive response at 125 Hz.

In Chapter 8 finger blood flow was similar in both hands following unilateral and bilateral vibration at 31.5 and 125 Hz and 5.5 to 22 ms^{-2} r.m.s. The similar vasoconstriction following unilateral and bilateral vibration suggests that vibration of two hands does not double the dose of vibration at the magnitudes investigated.

The results in this thesis are consistent with the hypothesis that vibration activates a centrally mediated vasoconstriction in both hands following vibration exposure applied to one hand.

9.5 The effect of vibration on finger blood flow excluding the effect of push force

Figure 9-3 contains a copy of the typical finger blood flow response to vibration based on the findings in the literature review (as Figure 2-7 in Chapter 2).

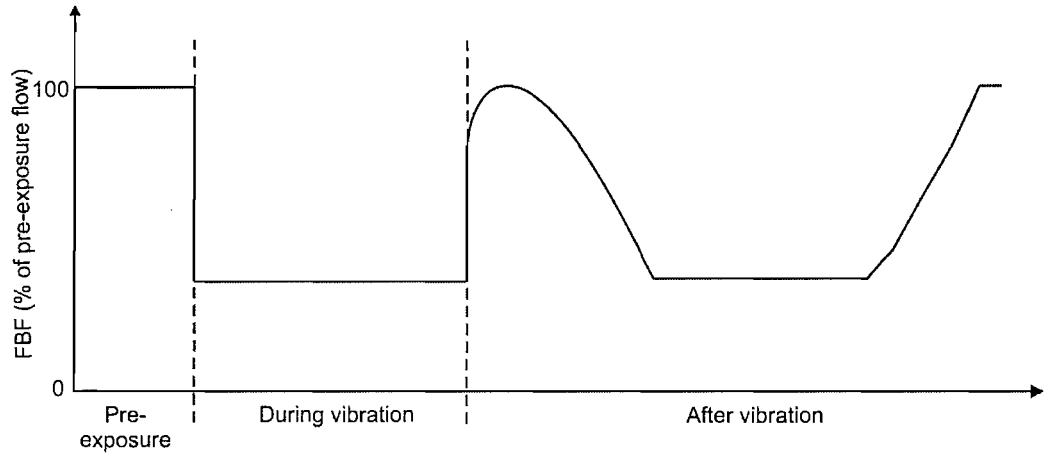


Figure 9-3 Typical response of finger blood flow before, during and after vibration exposure as described in previous studies in the literature review.

Based on the experimental findings of this thesis Figure 9-4 shows a new diagram of the typical response of finger blood flow to vibration exposure based on the results from this thesis.

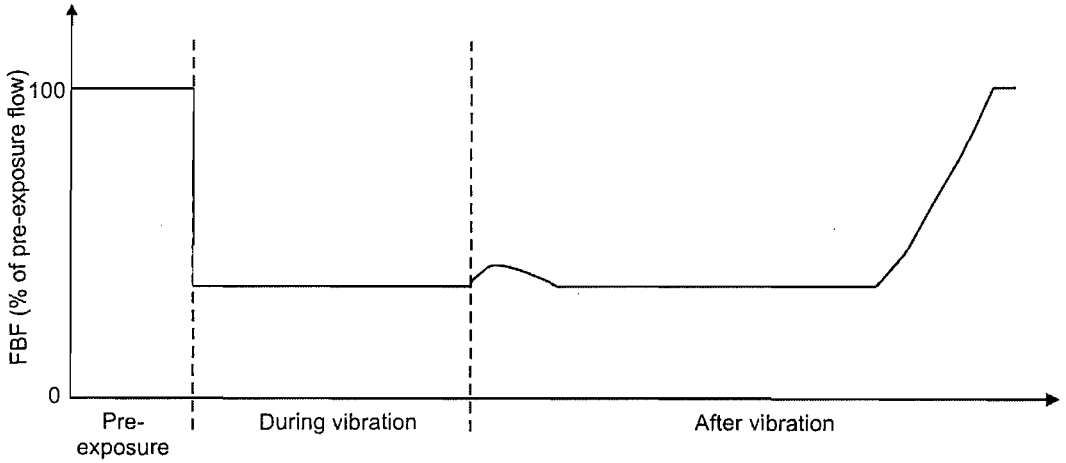


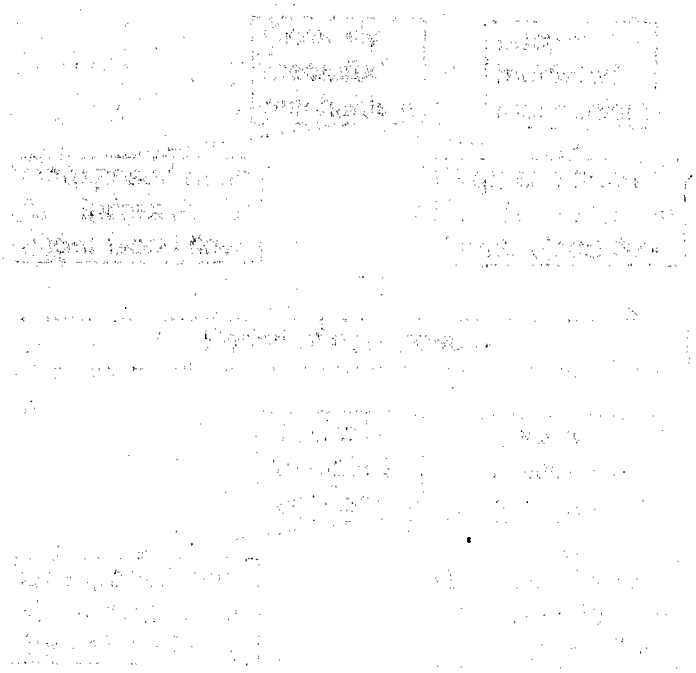
Figure 9-4 Typical reductions in finger blood flow before, during and after vibration exposure and when excluding the effect of push force on finger blood flow.

Figure 9-4 shows the reduction in finger blood flow effect during and after a vibration input excluding the effect of push force on finger blood flow.

When the effect of push force on finger blood flow is excluded the results in this thesis show that after vibration ceased finger blood flow continued to be reduced. The new diagram of a typical response to vibration includes a small temporary change in finger blood after vibration ceased compared to finger blood flow during vibration. The continued reduction in finger blood flow after vibration has ceased has implications for the understanding of the mechanisms controlling the blood flow (See 9.7).

A continued reduction in finger blood flow after vibration has ceased may contribute to the process of damage to the body that ultimately may develop into vibration-induced white finger.

9.6 Improvements to the model proposed in the literature review.



In Chapter 2, a diagrammatic interpretation of the effects of vibration on finger blood flow was presented based on a review of the literature (Figure 9-1). An explanation of Figure 9-1 is provided in the literature review (Chapter 2). The diagram (Figure 9-1) provided a structure around which the experiments in this thesis were constructed.

As a result of the findings of the experiments in this thesis, Figure 9-1 may be amended to show a new understanding of the effects of vibration on finger blood flow and the contributions to knowledge made by the work described in this thesis (Figure 9-2).

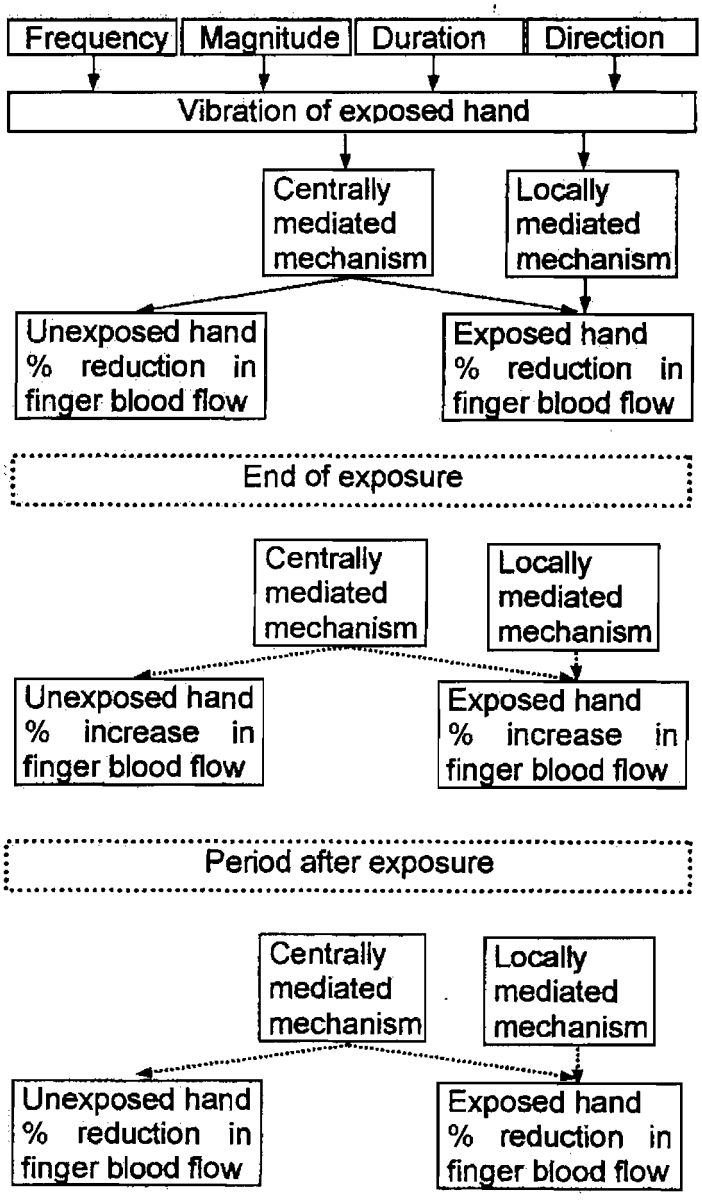


Figure 9-1 An interpretation of the variables affecting finger blood flow in the exposed and unexposed hands, during and after vibration exposure; based on studies considered in the literature review.

Figure 9-2 should aid comprehension of the findings in the literature and provide a framework for further research.

9.6.1 Previous observations of the effect of vibration on finger blood flow have been confounded by the effect of push force

Figure 9-2 shows push force as an independent variable that may influence finger blood flow. The strength of a reduction in finger blood flow is dependent on the force and the location where the force is applied to the hand. The application of a large push force to a hand may activate a centrally mediated vasoconstriction in both hands, whereas a small push force may not change blood flow in either hand (Figure 9-2). A push force applied to a finger may reduce flow in the exposed digit, whereas it is possible that a push force applied to the palm may not affect finger blood flow. From the findings in this thesis, Figure 9-2 shows that there may be a mechanical or physiological explanation for the reduction in blood flow in the exposed finger, due to push force.

With the removal of a push force, finger blood flow in the exposed finger returned to

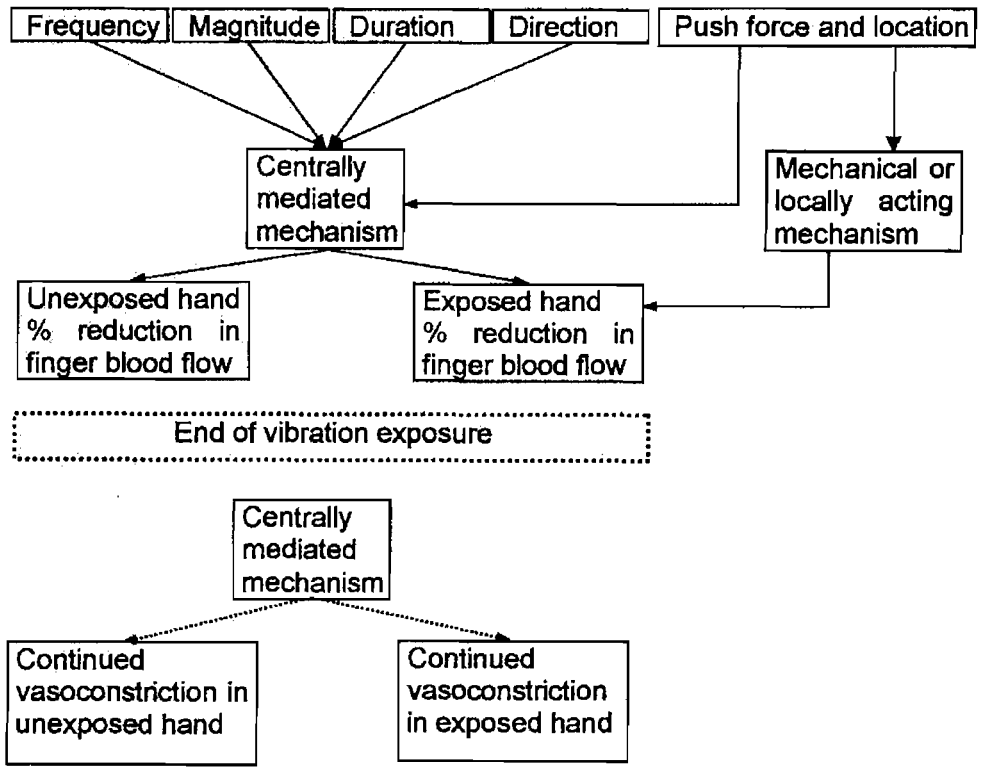


Figure 9-2 An interpretation of the variables changing the degree of vasoconstriction during and after vibration exposure, in the exposed and unexposed hands, based on studies from the literature review and the experimental results from this thesis.

pre-exposure levels.

9.6.2 Increasing the magnitude of vibration up to 15 ms^{-2} r.m.s. reduces finger blood flow.

The reduction in finger blood flow depends on the frequency of the vibration

The experiments in this thesis have shown that finger blood flow during and following vibration exposure is dependent on the magnitude and the frequency of the vibration. The literature suggested that the vascular response during vibration was dependent on vibration magnitude and frequency and that the vascular response after vibration was dependent on the vibration duration, magnitude and frequency. Previous studies have supposed that blood flow during and after vibration exposure are mediated by separate mechanisms and could not be predicted accurately using a simple predictive model. From the findings in this thesis, Figure 9-2 suggests that that the reductions in finger blood flow during and after vibration are mediated by the same mechanism. The mechanism controlling vasoconstriction during and after vibration is frequency-dependent and magnitude-dependent, within the ranges of magnitudes and frequencies investigated in this thesis. The vasoconstriction during vibration is indicative of the strength of vasoconstriction after vibration.

9.6.3 Vibration will produce the same reduction in finger blood flow in the exposed and unexposed hands

Instead of vibration producing a stronger vasoconstriction in the exposed hand than in the unexposed hand, this thesis concludes that vibration activates a centrally mediated mechanism and reduces finger blood flow equally in an exposed and unexposed hand. The role of locally mediated mechanisms in controlling vasoconstriction in the exposed hand seen in Figure 9-1 is absent in Figure 9-2.

In this series of experiments the removal of vibration did not produce a vasodilation in the exposed hand after every vibration exposure. This thesis concluded that a centrally mediated mechanism gradually returns blood flow in both hands to pre-exposure levels. The centrally and locally mediated vasodilation seen with the removal of vibration and force in previous studies in Figure 9-1 is absent in Figure 9-2.

9.7 Physiological mechanisms

From the theories proposed in the literature review, an explanation of the physiological mechanisms controlling the strength of vasoconstriction dependent on

the vibration magnitude and frequency, both during and after vibration can be hypothesised.

Bovenzi *et al.* (2000) proposed that the reduction in blood flow in both hands during unilateral vibration exposure may be due to a central sympathetic vasomotor reflex mechanism. The heightened sensitivity of finger blood flow to vibration at about 125 Hz is consistent with the frequency-dependency associated with the Pacinian mechanoreceptors (Welsh, 1980, Furuta *et al.*, 1991, Egan *et al.*, 1996, Bovenzi and Griffin, 1997).

The vibration magnitude may modify the rate at which a mechanoreceptors fire action potentials. Higher magnitudes may stimulate an increase in firing rate and lower magnitudes may stimulate a less frequent firing rates.

The firing rate of the afferent nerves may determine the firing rate of the efferent vascular sympathetic nerves either via the sympathetic nervous system or as a reflex arc. Increasing the activation of the sympathetic system would cause vasoconstriction (Aaronson *et al.,* 2005). Vibration of two hands caused the same degree of response as vibration of one hand (Chapter 8) and suggests that the physiological mechanisms respond to the characteristics of the vibration and that doubling the contact area does not necessarily trigger double the response.

The similar reduction in finger blood flow in an exposed and unexposed hand (Chapters 5 to 8) is consistent with a central sympathetic vasomotor mechanism as suggested by Bovenzi *et al.* (2000).

Bovenzi *et al.* (2000) hypothesised that the vasoconstriction following vibration may be due to a hyper-activity of the sympathetic nervous system induced by vibration, as also suggested by Olsen (1993). Bovenzi *et al.* (2000) alternatively hypothesise that the vasoconstriction occurring during recovery may be due to circulating vasopressor agents.

In Chapters 6 to 8 afferent vasoconstrictor agents may have stimulated the sympathetic nervous system to cause a neural efferent vasoconstrictor signal or may have triggered circulating vasoconstrictor agents to cause constriction of the smooth muscle of the digital arteries with increased vibration magnitude and frequency.

In Chapters 6 to 8 the cessation of vibration led to a frequency-dependent vasoconstriction. In Chapters 6 to 8 circulating vasopressor agents could have provided the continued vasoconstriction reported after vibration had ceased.

In this work, the frequency-dependence of finger blood flow during and after vibration is consistent with a vascular response that is initiated by frequency sensitive mechanoreceptors.

In Chapters 6 to 8 the finger blood flow following vibration exposure was similar in both hands which supports the hypothesis that the sympathetic nervous system may be controlling the peripheral blood flow response to vibration. Figure 9-2 infers that the same mechanism was responsible for the vascular response in both hands during and after vibration.

In describing the digital response to vibration without the confounding effect of push force the results of this thesis left questions unanswered which stimulate further research into the mechanisms activated by hand- transmitted vibration.

9.8 Possible areas for future work

9.8.1 Threshold

Based on Hyvärinen *et al.* (1973) identify each subject's vibrotactile threshold at 125 Hz. Investigate a possible link between vibrotactile sensitivity and finger blood flow by applying vibration just below the perception threshold, at threshold and just above the perception threshold.

Vibrate the palm at very low magnitudes at low frequencies (e.g. 8 Hz), to identify the magnitude at which vasoconstriction occurs.

9.8.2 Recovery

Investigate the recovery time required for finger blood flow to return to pre-exposure levels following vibration exposure. Vibration would be applied to the palm with different combinations of frequency and magnitude to show the duration of the vasoconstriction after vibration exposure. Would higher frequencies and magnitudes recover more slowly than lower frequencies and magnitudes?

9.8.3 Individual differences

Run repeated tests at the same frequency and magnitude conditions to see the intra-subject variability in blood flow response. Although measured finger blood flow differs

between people is the percentage change in blood flow during and after vibration independent of the measured finger blood flow?

9.8.4 Contact location

Compare the effect of contact location and size of contactors on finger blood flow (e.g. during vibration to the whole hand, to the fingers, to a finger, to the palm).

9.8.5 Method

Standardise the interpretation of the arterial inflow slopes used with venous occlusion plethysmography.

9.8.6 Vasopressor agents

Measure levels of circulating vasopressor agents in the blood during and after vibration exposure with different combinations of vibration frequency and magnitude. Concentrations of vasopressor agents will indicate whether vibration is triggering a humoral response.

9.8.7 Sympathectomy or nerve block

The removal of vaso constrictor nerves or a nerve block would minimise the sympathetic control of digital blood flow. A less marked reduction in finger blood flow during and after vibration exposure in the subject's with the nerve block compared to healthy controls would show that the vasoconstriction is principally controlled by the sympathetic nervous system.

9.8.8 Investigate the links between acute and chronic vascular symptoms

Epidemiological studies could chronicle vibration exposure and the development of the vascular symptoms of hand-arm vibration syndrome (HAVS). Changes in the strength of vasoconstriction with increasing years of vibration exposure could be monitored. Studies using new employees without a history of tool exposure could be used to investigate the onset of symptoms following exposure to vibration of known vibration magnitudes, frequencies, and durations.

The onset of neurological symptoms of HAVS, such as increased vibrotactile and thermotactile thresholds, could be monitored and compared with the onset of vascular symptoms.

9.9 Implications of this thesis

It is hoped that the identification of the vibration frequencies and magnitudes that are most vasoactive (within the range investigated) will ultimately lead to the minimisation of injury resulting from exposure to hand-transmitted vibration.

Ideally, tool manufacturers will design vibrating tools that do not transmit vibration at frequencies and magnitudes identified as producing strong vasoconstriction during and after vibration exposure. The dependence of finger blood flow on the vibration frequency and magnitude (Chapters 6 and 7) provides strong evidence for changing the types of vibration to which tool users are exposed. Exposure to high frequency and high magnitude vibration will cause stronger vasoconstriction during and after vibration exposure than exposure to low frequency and low magnitude vibration (within the range investigated). Vibration at high frequencies and high magnitudes could be considered to be putting users at a higher risk of potential long-term injury than people exposed to vibration at low frequencies and low magnitudes.

Standards and guidelines with more accurate frequency weighting curves and incorporating force as a risk factor affecting the transmission of hand-transmitted vibration may help control the risks to people using vibrating tools. The current frequency-weighting in ISO 5349 (2001) was based on the sensitivity of sensory perception of vibration. The dependence of finger blood flow on frequency during and after exposure to vibration with equal frequency-weighted acceleration (Chapters 6 and 7) indicated that the W_h frequency-weighting in ISO 5349 (2001) does not represent the sensitivity of the peripheral blood flow to vibration. Chapter 7 shows that the vascular response was underestimated by the frequency-weighting. This thesis suggests that vibration can produce a reduction in finger blood flow below the level of sensory perception. It is possible that more people in the workplace are at risk of reductions in blood flow during exposure to vibration below threshold level.

It is suggested that the frequency-weightings in ISO 5349 (2001) are reassessed to reflect the dependence of finger blood flow to vibration frequency as shown in Figure 7-5.

Appendix C discusses how the relations between displacement, velocity and acceleration vary with frequency and how this relates to the frequency-weighting in ISO 5349 (2001).

The vasoconstriction occurring after vibration exposure (Chapters 5 to 8) was frequency dependent and gives support for a frequency-weighting to prevent vibration exposure that can lead to VWF. The sustained vasoconstriction in the exposed and unexposed hand after vibration has ceased is consistent with an endocrine response. Further investigation into the endocrine function during and after vibration exposure may give greater understanding of the way to treat VWF or about individual susceptibility to damage from vibration exposure.

The vasoconstriction occurring from the application of push force to the hand or fingers (Chapters 5 to 8) should indicate that push force may affect the transmission of vibration to the tool user. The distribution of blanching on the digits of a tool user is not necessarily similar on both hands. Chapter 6 found that vasoconstriction occurred when the finger was in contact with the vibrating platform. Vasoconstriction did not occur when the palm was in contact with the vibrating platform. It can be speculated that push force may affect the development of abnormal vasoconstriction during vibration or cold exposure.

9.10 Summary of Discussion

It was known that VWF is associated with long-term exposure to vibration possibly in association with other factors.

In this work it was discovered that previous studies of the effect of vibration on finger blood flow may have been confounded to some extent by push force. When push force was controlled it was discovered that:

a) The frequency-weighting in ISO 5349 (2001) based on perception thresholds was not correct for anticipating the vascular response during and after vibration exposure,

b) Finger blood flow remained reduced after vibration had ceased

c) Evidence exists for a centrally controlling mechanism of finger blood flow in response to vibration

Points b) and c) suggest that the endocrine system (as a slower acting system) is involved, additional to any neural reflexes, or purely mechanical effects.

There were limitations to the extent that the results in this thesis can be applied to an understanding of the development of vibration white finger.

A potential limitation of the experiments in Chapters 5 to 8 was that acute vibration was applied whereas VWF occurs after long-term vibration exposure. It was assumed that the magnitude and frequency dependence of finger blood flow during acute vibration would be similar to the dependence of finger blood flow on magnitude and frequency as a result of long-term vibration exposure. The link between acute effects and chronic effects of vibration exposure is unknown.

A potential limitation of the experiments in Chapters 5 to 8 was that the vasoconstriction that occurred during and after acute vibration exposure did not approach the level of vasoconstriction reported during an attack of vibration-induced white finger. Chapters 5 to 8 found a maximum percentage reduction in finger blood flow compared to pre-exposure finger blood flow of 30 to 40%. During an attack of vibration-induced white finger there is total occlusion resulting in blanching in the affected areas. The level of occlusion seen during a blanching attack was not able to be reproduced in the laboratory at any frequency and magnitude of vibration used. Other factors additional to acute vibration could be involved in the development of the total occlusion that is typical during a blanching attack of VWF.

It is speculated that higher frequencies or magnitudes of vibration could produce the strength of vasoconstriction seen during an attack of VWF.

It is speculated that the temperature of the working environment of tool users could be a cofactor affecting vasoconstriction during vibration exposure. Cold weather is known to cause vasoconstriction in the extremities e.g. fingers, toes. Vasoconstriction due to cold could enhance the vasoconstriction that is due to vibration. In the experiments in this thesis the temperature of the laboratory was kept between 25.0 to 30.0 °C to ensure reductions in blood flow were due to vibration and not the temperature of the environment.

It is speculated that there is great variability in individual sensitivity to vibration. Some lifestyle habits e.g. smoking could increase the likelihood of long-term vibration injury. The subject's used in the laboratory studies of this thesis were healthy males with no known medical disorders (see Appendix A for the medical questionnaire). Lifestyle factors and individual sensitivity to vibration injury is not controlled in the workplace.

In the working environment a vibrating tool can be held in any position relative to the heart. In Chapter 4 the height of the hand relative to the heart was found to affect finger blood flow. In the experiments in Chapters 5 to 8 subjects lay supine

throughout the experimental session with the hand at heart height to minimise the effect of hand height relative to the heart. The use of vibrating tools above or below the level of the heart could affect the vascular response to vibration. Tool position and user posture has been linked to the musculo-skeletal component of hand-arm vibration syndrome.

The centrally mediated vasoconstriction produced in both hands by vibration exposure to one hand in Chapters 5 to 8 suggests that vibration white finger could develop in the exposed hand and to a similar degree in the unexposed hand. However, the distribution of whiteness on the fingers of sufferers of VWF is not necessarily similar on both hands. The results of this thesis show that push force during vibration exposure can change the vasoconstriction occurring during acute vibration exposure. It is not known whether long-term exposure to push force can affect the response to vibration.

CHAPTER 10

CONCLUSIONS

The overall aim of this thesis was to improve understanding of the effect of vibration on finger blood flow by investigating the dependence on vibration frequency and magnitude (Chapter 2).

The experiments have shown that the contact location and force between the vibrating surface and the finger or hand can affect finger blood flow irrespective of the vibration (Chapters 5, 6, 7 and 8). The effect of a push force on finger blood flow during and after vibration exposure is dependent on the force and location of the application of the force (Chapter 6). Push force and vibration can have a cumulative vasoactive effect on finger blood flow (Chapter 6).

Without a confounding influence of push force on finger blood flow, exposure of one hand to vibration caused the same reduction in blood flow in both the exposed hand and the unexposed hand, both during and after vibration exposure (Chapters 6, 7 and 8).

After vibration ceased a slight vasodilation compared to finger blood flow during vibration exposure occurred in both hands.

Vibration of one hand caused vasoconstriction in both the exposed and the unexposed hand during vibration that was dependent on the frequency and magnitude of the vibration (Chapters 6 and 7).

By using a linearly increasing magnitude of vibration, it was found that finger blood flow during vibration was approximately inversely proportional to the vibration velocity magnitude (Chapter 5, 6 and 7). As the velocity increased from 0 to 11 ms^{-1} r.m.s. finger blood flow reduced.

Finger blood flow during bilateral vibration showed some dependence on acceleration magnitude (Chapter 8).

Higher frequencies of hand-transmitted vibration (e.g. 125 Hz to 315 Hz) with constant velocity caused a stronger reduction in blood flow than lower frequencies (e.g. 16 Hz to 31.5 Hz) both during and after vibration exposure of one hand (Chapters 6 and 7).

After the end of exposure to vibration having the same velocity at each frequency, the continued vasoconstriction in both hands was dependent on the frequency of vibration (Chapters 6 and 7).

During and after vibration of two hands with the same acceleration at both 31.5 and 125 Hz, blood flow seemed independent of the vibration frequency (Chapter 8).

Further work is required to understand the acute effect on finger blood flow of vibration of multiple locations, interactions between vibration characteristics and the mechanisms controlling the response to vibration so an improved predictive dose-response can be calculated (Chapter 9).

It is concluded that vasoconstriction in the hands during and after vibration is primarily determined by a centrally mediated mechanism.

APPENDIX A

Dear Subject

Please could I request that you do not drink coffee, tea, coke or alcohol avoid smoking and avoid using vibrating tools for 2 hours prior to each experimental testing, as this can affect blood flow.

Your testing times are on:

(1) Thursday 28/10/04 (10:00)

Miss one week

(2) Wednesday 10/11/04 (10:15)

Miss one week

(3) Monday 22/11/04 (10:15)
(4) Tuesday 23/11/04 (10:15)
(5) Wednesday 24/11/04 (10:15)
(5) Friday 26/11/04 (10:15)

The experiment is located in Room 1061 which is reached through Room 1059.

Many thanks,
Lexi

Tel: 023 8059 4962
E-mail: ljlw@soton.ac.uk

Subject Medical Questionnaire

Name: Date:

Do you smoke? Yes/No .....Cigs per day

Have you ever suffered from cold hands? Yes/No

Do you suffer from any connective tissue diseases? Yes/No

Do you suffer from any diseases of the circulation? Yes/No

Do you suffer from any diseases of the nervous system? Yes/No

Have you ever suffered an injury to your fingers, hands, arms, neck? Yes/No

Approximately how many hours each year are you exposed to hand-transmitted vibration?.....

Age;.....yrs.....months Height.....m Ethnic Group:.....
Date of birth: Weight.....kg

Anthropometric data

		Right middle	Right Little	Left Middle
Length	Finger			
	Proximal			
	Medial			
	Distal			
Width	Distal			
	Medial			
Depth	Distal			
	Medial			

Any other information:

APPENDIX B

APPENDIX B

MEASUREMENT OF PERIPHERAL BLOOD FLOW DURING WHOLE BODY VIBRATION

B.1 INTRODUCTION

Several studies exposing one hand of healthy subjects to hand-transmitted vibration show an acute decrease in blood flow during vibration exposure. A decrease in flow during vibration has also been recorded in the non-exposed contralateral hand (e.g. Bovenzi *et al.*, 1995, 1998, 2000), suggesting the influence of a central mechanism for the effect of vibration on peripheral circulation.

Long-term effects of exposure to whole-body vibration (e.g. pilots, drivers) may be associated with musculo-skeletal disorders (such as back pain), intestinal disorders, secondary disorders of the peripheral nervous system and, possibly, a higher incidence of peripheral venous disorders such as haemorrhoids and varicosis (Seidel *et al.*, 1984). Rittweger *et al.* (2000) found an increase in systolic blood pressure, a decrease in diastolic blood pressure and a decrease in oxygen intake after combined whole-body vibration (26 Hz at 147 ms^{-2} peak acceleration) and exercise, compared to exercise alone. Hood *et al.* (1966) found increases in arterial and central venous mean blood pressure, cardiac index and heart rate during a range of acute vibration exposures (2 to 12 Hz with peak accelerations of 0.6 and 1.2 g for 5 minutes per condition). Kerschan-Schindl *et al.* (2001) found an increase in the mean blood flow of the popliteal artery after acute vibration exposure to 26 Hz at 78 ms^{-2}peak acceleration, for 9 minutes, with subjects in a standing position. Can exposure to acute whole-body vibration affect peripheral blood flow in a similar way that hand-transmitted vibration affects peripheral blood flow?

In the work place people are often exposed to whole-body vibration before, at the same time as, or shortly after, exposure to hand-transmitted vibration. In experimental research people are exposed to whole-body vibration when travelling in a car, bus or train to the laboratory. An understanding of the effects of whole-body vibration on peripheral blood flow may aid understanding of any interaction between the effects of the two stimuli.

The purpose of this study was to investigate the effects of two frequencies of whole-body vibration on peripheral blood flow in the fingers and toe, in comparison with a static control. The hypothesis were:

(i) Blood flow measured during and after vibration exposure would differ to blood flow measured in a static control condition at an equivalent time.

(ii) Blood flow measured during and after vibration exposure would differ from blood flow measured before vibration exposure.

(iii) Changes in blood flow would depend on the vibration characteristics.

B.2 METHOD

B.2.1 Subjects

Ten healthy male subjects from the staff and students of the University of Southampton were enrolled in the study. They were not affected by finger symptoms, exposed to occupational vibration, or using medicines at the time of the study. The subjects read a list of medical contraindications and gave written informed consent to participation in the study. Subjects were requested to avoid coffee, tea, cola, smoking, alcohol and hand-transmitted vibration for at least two hours prior to testing. The dimensions of the left index finger, left ring finger and right toe were measured with vernier callipers to an accuracy of 0.5 mm. The volumes and surface areas of the fingers were then calculated according to the method suggested by Garrett (1970).

B.2.2 Experimental design

Subjects were seated on a rigid, slightly contoured, wooden seat mounted on a VP180 Derritron vibrator. The legs were supported on a stationary support with the knees bent at 90° and the upper surface of the upper legs horizontal. The left hand was supported at heart height with the arm outstretched. Shoes, socks, watches and jewellery were removed. Subjects wore light clothing.

Subjects were exposed to three conditions on separate days: a control condition with no vibration, vertical vibration with 8 Hz at 1.0 ms^{-2} r.m.s., and vertical vibration with 63 Hz at 4.0 ms^{-2} r.m.s., presented in a balanced order.

Blood flow (BF) was measured in the left index finger, left ring finger and right toe. Finger skin temperature (FST) was measured in the left ring finger. The BF, FST and room temperature (RT) measurements were taken at the 15^{th}, 17^{th} and last minute of a 20-minute acclimatisation period, at the 1^{st}, 5^{th}, 9^{th}, 13^{th} and 17^{th} minute of a 17-

minute vibration exposure, and at the first minute of recovery and every four subsequent minutes until the end of a 40-minute recovery period.

The static control condition involved the same procedure with the vibration magnitude reduced to zero. Each condition lasted 77 minutes.

B.2.3 Blood flow measurement

Peripheral blood flow was measured using strain gauge venous occlusion plethysmography according to the technique proposed by Greenfield *et al.* (1963).

A flexible plastic cuff was fitted snugly around the proximal phalanges of the left index finger, left ring finger and right toe. The soft plastic tubes of the digital cuffs (40 cm in length) were connected to a manifold connected by wider tubing (85 cm in length) to the plethysmograph (*HVLab* Multi-Channel). Mercury-in-silastic strain gauges were positioned between the nail and the knuckle of each occluded digit. Strain gauges were chosen according to size, so that they were in slight extension before occlusion. The same strain gauges were used for a subject in all three experimental conditions.

On instruction, the plethysmograph inflated the air cuff to the desired air pressure, 60 mmHg, applying venous occlusion to the finger for 8 seconds. Venous occlusion stopped the blood leaving the finger beneath the cuff, but still allowed arterial inflow. During venous occlusion, the plethysmograph indicated the increasing finger volume by measuring the corresponding increase in resistance of the strain gauge. The change in resistance (assumed to be proportional to strain) was recorded as a relative percentage change from the baseline resistance measured during a calibration pulse immediately prior to occlusion.

At each measurement, all three digits were occluded simultaneously and blood flow at each site was recorded. The finger and toe blood flow were measured two or three times at each measurement and the average taken and used for the statistical analysis. Blood flow was expressed as ml/100ml/s (millilitres of blood per 100 millilitres of tissue per second).

Finger skin temperature was measured (°C) by a thermocouple attached by micro pore tape to the distal phalanx of the left ring finger. Finger skin temperature and room temperature were measured to an accuracy of 0.5 °C.

B.2.4 Statistical methods

Data analysis was conducted with SPSS (version.10.0). The data were summarised with the median as a measure of central tendency and the inter-quartile range as a

measures of dispersion. Non-parametric tests (Friedman test for *k*-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed in the statistical analysis to test for differences in blood flow between test conditions before vibration, during vibration and during recovery. Friedman and Wilcoxon tests were also used to compare pre-exposure blood flow to the blood flow during exposure to vibration, and to compare blood flow during exposure to blood flow during recovery. Correlations were determined within subjects between blood flow in the control condition and in the 8 Hz condition, between the control condition and 63 Hz condition and between the 8 Hz condition and 63 Hz condition.

B.3 RESULTS

B.3.1 Finger blood flow

The three pre-exposure blood flow measurements (i.e. those before exposure to vibration) are labelled FBF1 to FBF3 (Figure1).

The five blood flow measurements during exposure are labelled FBF4 to FBF8. The eleven blood flow measurements during the recovery period are labelled FBF9 to FBF19.

B.3.2 Effect of test condition

Figure 1 shows the median blood flow of all subjects in the ring finger, index finger and toe, in the static control condition, the 8 Hz condition and the 63 Hz condition.

Wilcoxon matched-pairs signed ranks tests were employed to test for differences in blood flow between test conditions. In view of the large number of comparisons, a significance level of 1% (i.e. $p<0.01$) was chosen for the criterion of significance.

B.3.3 Before Exposure

For the three measures prior to vibration exposure there were no significant differences in blood flow between the index and ring fingers within a condition or between conditions within a finger (apart from the first pre-exposure measure (FBF1), when the blood flow in the static control condition was marginally significantly greater than in the 63 Hz condition ($p=0.028$).

Within digits, correlations between blood flows measured in individual subjects in the three different conditions were mainly positive. However, most of the correlations were not even marginally statistically significant ($p>0.05$). Exceptions were in the index finger, where pre-exposure blood flow FBF1 in the static control condition was positively correlated with FBF1 in the 63 Hz condition with marginal significance

(p=0.038). Blood flow during FBF3 in the static control condition was marginally significantly correlated with FBF3 in the 8 Hz condition (p=0.022). Similarly, there were mainly positive correlations between blood flow within digits within the same condition, however most of these were only marginally significant (p<0.05).

There were no significant differences between the blood flow in the index and ring fingers, for any of the three pre-exposure measures during any of the three conditions. Except in the 8 Hz condition, where blood flows in the ring and index finger were significantly different for the three pre-exposure measures (p=0.005).

B.3.4 During Vibration Exposure

The Wilcoxon test was employed to test for differences in blood flow between test conditions during the vibration exposure period. For the five measures of blood flow during vibration exposure within digits, there was no significant difference between the static control and either the 8 Hz condition or the 63 Hz condition (p>0.139). Exceptions were marginally significant differences in blood flow between the 63 Hz and 8 Hz conditions in the third measurement during vibration (i.e. BFD3) in the ring and index finger (p=0.016 and p=0.022, respectively).

Within digits, correlations between blood flow measured in individual subjects in the three conditions were mainly positive. However, most of the correlations were not even marginally statistically significant (p>0.05).

B.3.5 During recovery

A Wilcoxon test was employed to test for differences in blood flow between test conditions during the recovery period following the vibration exposure period. For the eleven measures during recovery there was no significant difference in blood flow within fingers between conditions. Exceptions were a marginally significantly greater blood flow in the index finger in the control condition at FBF13 than in the 63 Hz condition at FBF13 (p=0.047) and a marginally significantly greater blood flow in the index finger in the control condition at FBF16 than in the 63 Hz condition at FBF16, (p=0.037).

Similarly, significantly greater blood flows were measured in the 8 Hz condition than in the 63 Hz condition at FBF18 in the index finger (p=0.037) and in the ring finger (p=0.01).

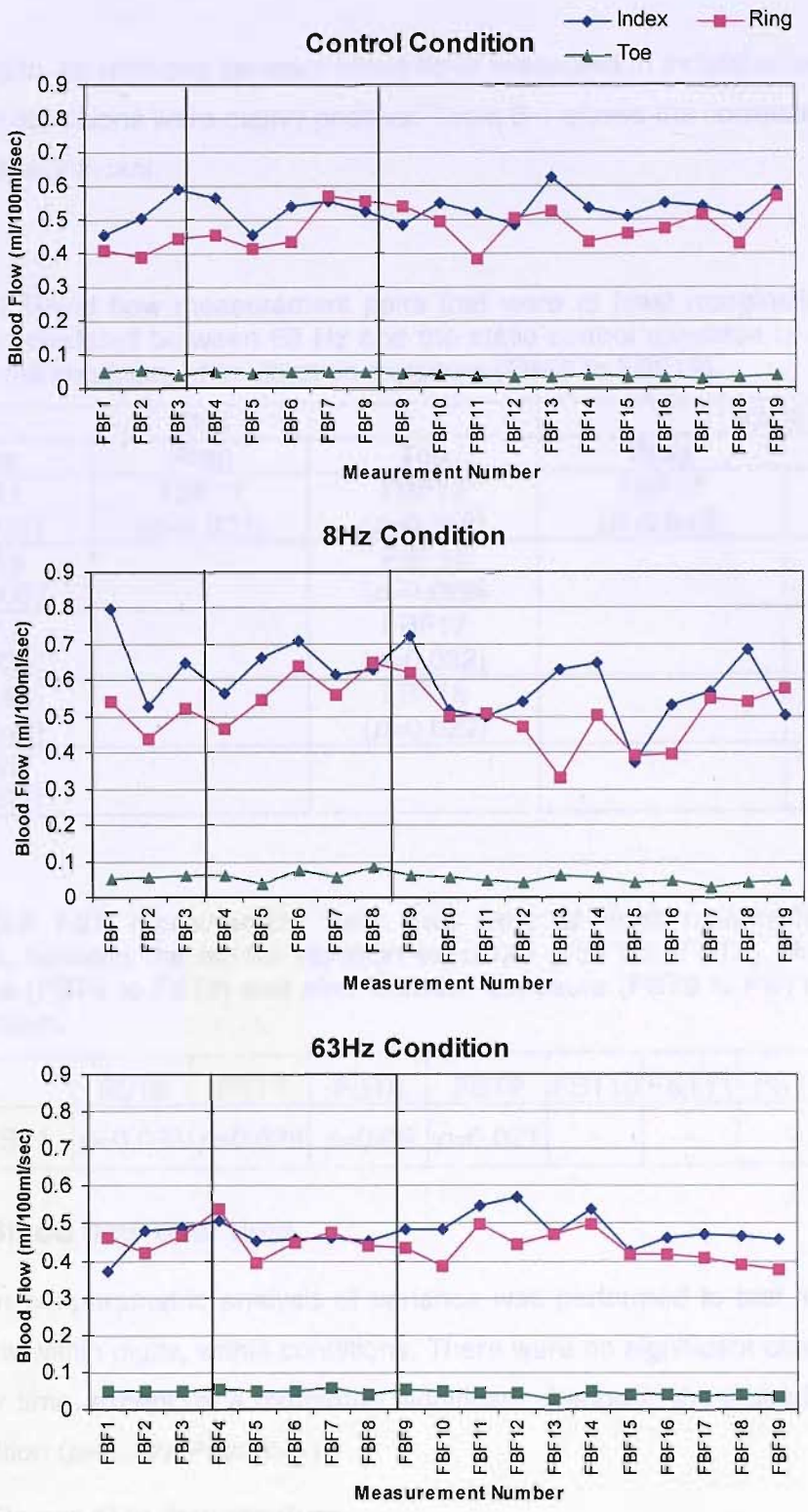


Figure B-1 Median digital blood flow for the toe, ring finger and index finger measured in 10 healthy subjects, in three test conditions: before vibration (FBF1 to FBF3), during vibration (FBF4 to FBF8) and after exposure (FBF9 to FBF19).

Within digits, correlations between blood flows measured in individual subjects in the three test conditions were mainly positive. Table B-1 shows the correlations that were marginally significant.

Table B-1 Blood flow measurement pairs that were at least marginally significantly positively correlated between 63 Hz and the static control condition or 8 Hz and the static control condition, after vibration exposure (FBF9 to FBF19).

8Hz			63Hz	
Index	**Ring**	**Toe**	**Ring**	**Toe**
FBF11 (p=0.043)	FBF11 (p=0.021)	FBF12 (p=0.019)	FBF17 (p=0.043)	FBF12 (p=0.024)
FBF13 (p=0.006)		FBF14 (p=0.029)		
FBF17 (p=0.025)		FBF17 (p=0.022)		
FBF180 (p=0.043)		FBF18 (p=0.029)		
FBF19 (p=0.022)				

Table B-2 FST measurement pairs that were at least marginally significantly different, between the before vibration exposure (FST1 to FST3), during vibration exposure (FST4 to FST8) and after vibration exposure (FST9 to FST19), for the 63 Hz condition.

	FST6	FST7	FST8	FST9	FST10	FST11	FST15	FST16
63Hz FST1	p=0.033	p=0.028	p=0.09	p=0.021	-	-	-	-

B.3.6 Blood flow over time

Friedman nonparametric analysis of variance was performed to test for changes in blood flow within digits, within conditions. There were no significant changes in blood flow over time, except for a marginally significant change in the index finger in the 8 Hz condition (p=0.060, Friedman).

B.3.7 Finger skin temperature

The finger skin temperature (FST), measured on the distal phalanx of the left ring finger at the same time as the blood flow was measured, was labelled as follows: pre-exposure finger skin temperature measurements are labelled FST1 to FST3; finger skin temperature during exposure is labelled FST4 to FST8; and finger skin temperature during recovery is labelled FST9 to FST19.

Wilcoxon tests were employed to test for differences in FST between test conditions before vibration exposure. For the three pre-exposure FST measurements, five during exposure FST measurements and eleven recovery FST measurements, there were no significant differences, between conditions (p>0.07) or over time within a condition. Exceptions were marginally significantly different FSTs in the 8 Hz condition than in the static control condition at FSTB2, (p=0.047) and FSTB3 (p=0.041). In the 63 Hz condition, FST varied significantly within the entire condition (p=0.01, Friedman). Wilcoxon tests found no significant difference between any pre-exposure FST measurement and any FST measurement during vibration, or any FST measurement after vibration (p>0.05). Exceptions occurred only at 63 Hz and are shown in Table B-2.

B.4 CORRELATION BETWEEN BLOOD FLOW AND FINGER SKIN TEMPERATURE

Correlations in the ring finger between FST and blood flow within conditions were mainly positive. However, most of the correlations were not even marginally significant (p>0.05). Exceptions were positive correlations in the control condition before exposure (FBF2, p=0.019) and during exposure (FBF2, p=0.013); in the 8 Hz condition, during exposure (FBF6, p=0.037) and in the 63 Hz condition a negative correlation during the recovery period (FBF16, p=0.011).

B.4.1.1 Room temperature

The median (range) of room temperature was 27.1° (26.7° to 28.0°) in the static condition, 27.15° (24.8° to 28.0°) in the 8 Hz condition and 27.25° (26.1° to 28.2°) in the 63 Hz condition. There were no significant differences in room temperature between the three conditions (p>0.137, Wilcoxon).

B.5 DISCUSSION

The general trend in pre-exposure measures in all digits was that there was no difference in blood flow between the control condition and the two vibration conditions. The correlations within digits within conditions suggest that the blood flow being used as a pre-exposure baseline is stable and representative of the subject's typical blood flow in each session.

Blood flows during vibration exposure at 8 Hz and 63 Hz did not significantly differ from blood flow at the equivalent time in the static control condition. The lack of a change in blood flow in either finger during vibration exposure at both 8 Hz and 63 Hz compared to the control condition, suggests that the vibration stimuli did not activate

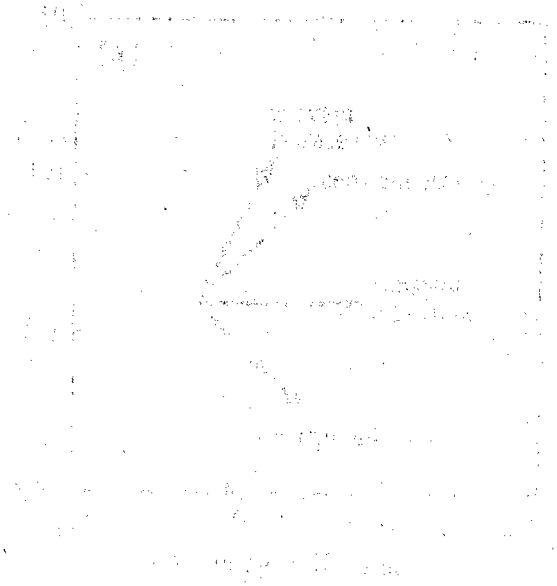
a strong physiological response mechanism that altered peripheral blood flow from normal blood flow variations.

Within conditions, no considerable difference in blood flow was found between the acclimatisation, exposure and recovery periods. This is very different to the pattern of blood flow exhibited during exposure to hand-transmitted vibration, where there is reduced blood flow during exposure, followed by immediate vasodilation and then the gradual onset of vasoconstriction followed by gradual return to pre-exposure blood flow levels after many minutes of recovery (Bovenzi *et al.*, 1995, 1997, 2000).

B.6 CONCLUSION

Peripheral blood flow measured during and after vibration exposure to whole-body vibration at 8 Hz and 63 Hz did not significantly differ from blood flow measured at the equivalent time in a static control condition. Any affects of whole-body vibration on digital blood flow in this study appear to have been transient and mild, particularly in comparison with previously reported reductions in blood flow during and following exposures to hand-transmitted vibration.

APPENDIX C



APPENDIX C

HOW THE RELATIONS BETWEEN DISPLACEMENT, VELOCITY AND ACCELERATION VARY WITH FREQUENCY AND HOW THIS RELATES TO THE FREQUENCY WEIGHTING IN ISO 5349 (2001)

C-1 How the relations between displacement, velocity and acceleration vary with frequency

The relationship between displacement, velocity and acceleration varies with frequency. Figure C-1 shows simple representations of the effect of vibration frequency: (a) change in acceleration associated with constant jerk, constant acceleration, constant velocity and constant displacement, and (b) the formation of a single contour showing the magnitudes of vibration at different frequencies with might cause similar effects (Griffin, 1990).

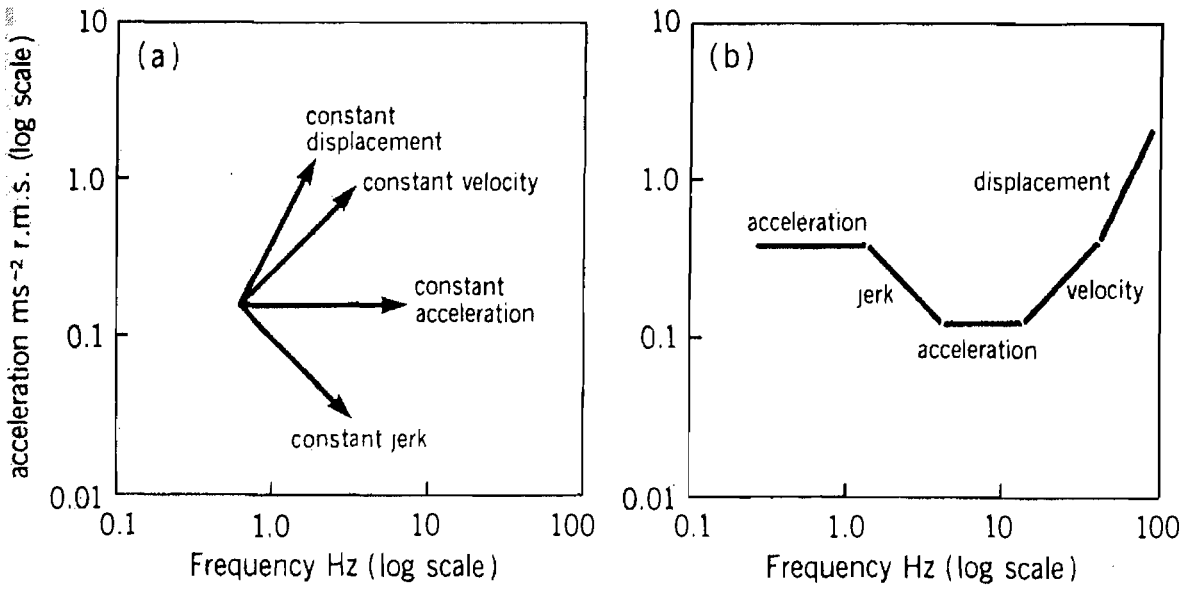


Figure C-1 Simple representations of the effect of vibration frequency: (a) change in acceleration associated with constant jerk, constant acceleration, constant velocity and constant displacement; (b) formation of a single contour showing the magnitudes of vibration at different frequencies that might cause similar effects (Griffin, 1990).

The relationship between frequency, acceleration, velocity and displacement can be implied from the formulae in Table C-1.

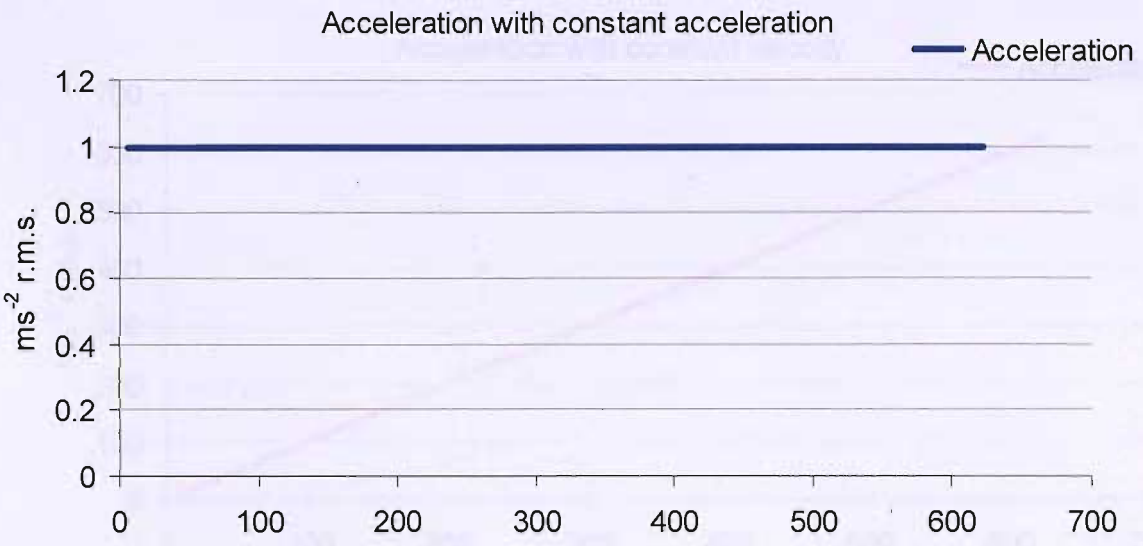
Table C-1 shows that for a sinusoidal oscillation of constant acceleration, the velocity is inversely proportional to the frequency and the displacement is inversely proportional to the square of the frequency. Figure C-2 shows graphically the way in which the velocity and displacement of a sinusoidal oscillation of constant acceleration vary with frequency.

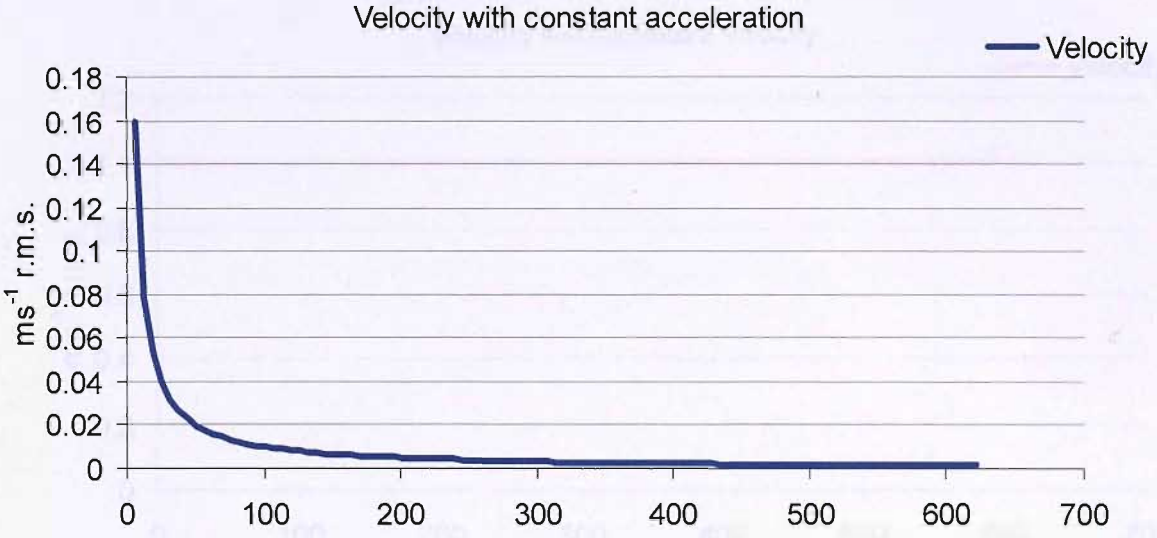
Table C-1 shows that for a sinusoidal oscillation of constant velocity, the acceleration is proportional to the frequency and the displacement is inversely proportional to the frequency. Figure C-3 shows the change in acceleration and displacement with constant velocity and varying frequency.

Table C-1 shows that for a sinusoidal oscillation of constant displacement, the acceleration is proportional to the square of the frequency and the velocity is proportional to the frequency. Figure C-4 shows the change in acceleration and velocity with constant displacement and varying frequency.

Table C-1 Conversion between peak displacement, X, peak velocity, V, and peak acceleration, A, for sinusoidal oscillation of frequency, f (in Hz)

	Displacement, X	Velocity, V	Acceleration, A
Displacement, X	$X = X$	$X = \frac{V}{2\pi f}$	$X = \frac{A}{(2\pi f)^2}$
Velocity, V	$V = 2\pi f X$	$V = V$	$V = \frac{A}{2\pi f}$
Acceleration, A	$A = (2\pi f)^2 X$	$A = 2\pi f V$	$A = A$





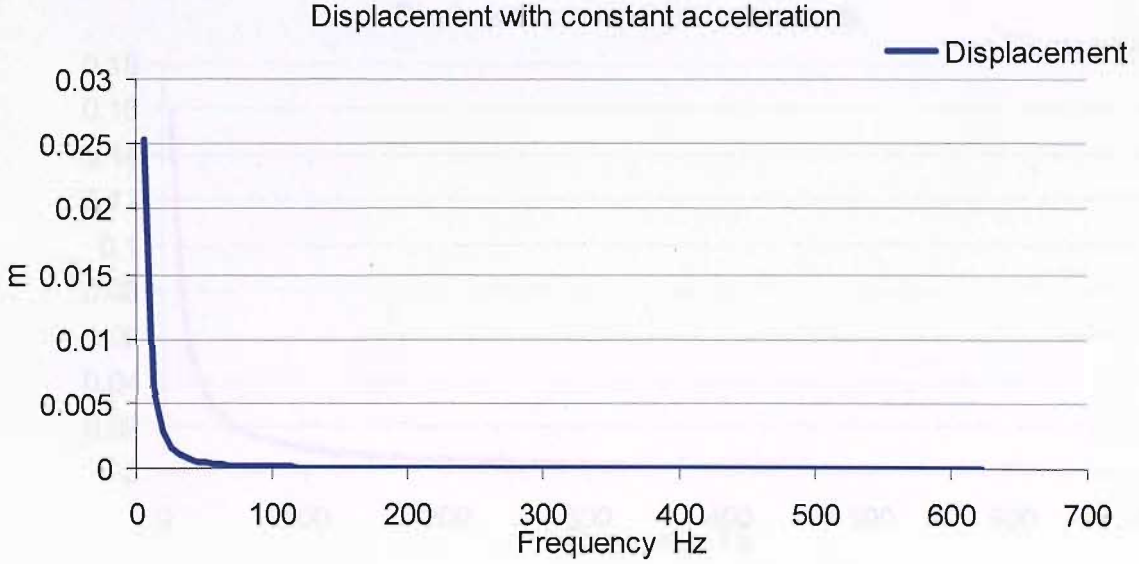


Figure C-2 Changes in velocity and displacement with constant acceleration and varying frequency.

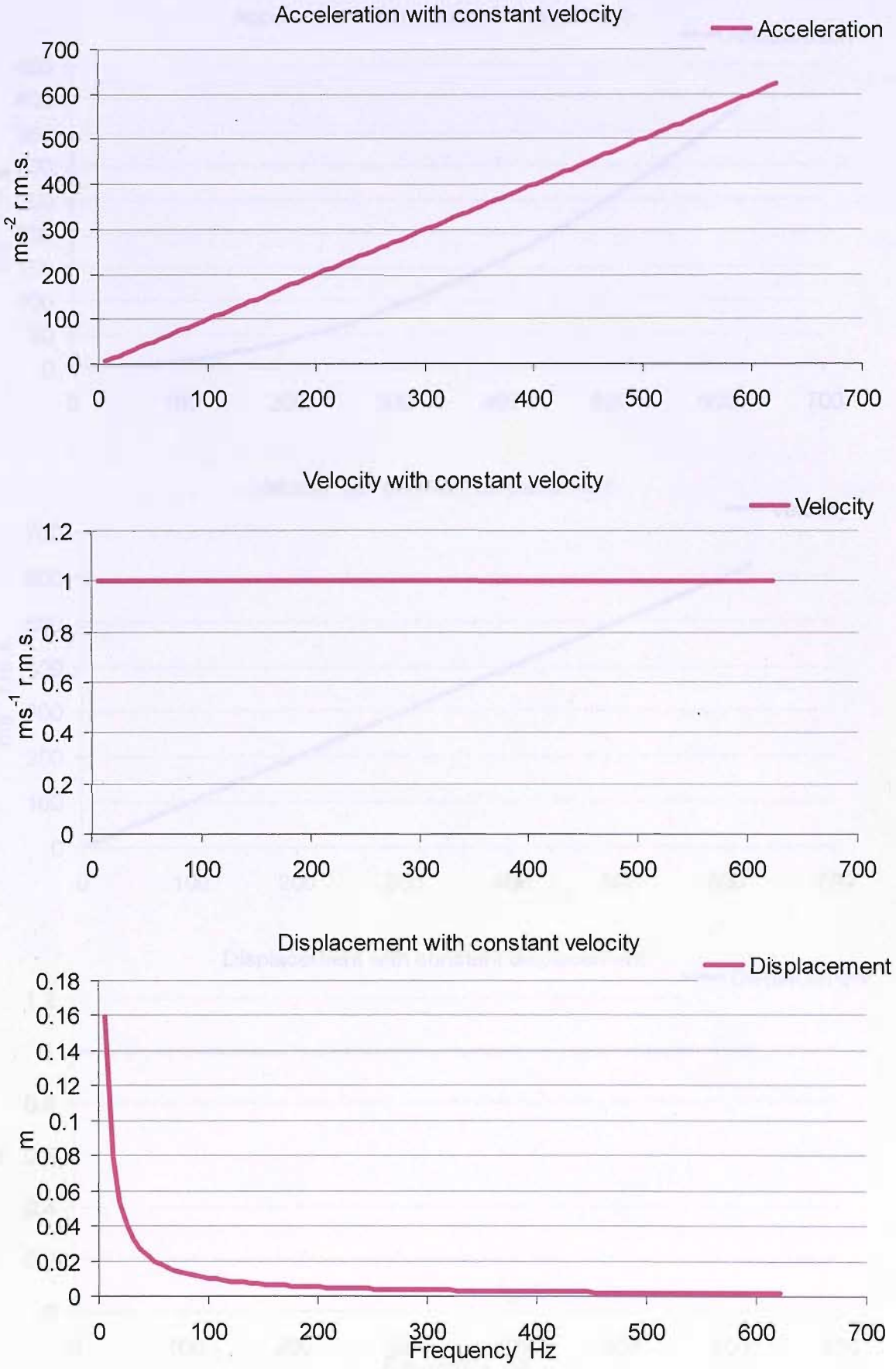


Figure C-3 Changes in acceleration and displacement with constant velocity and varying frequency.

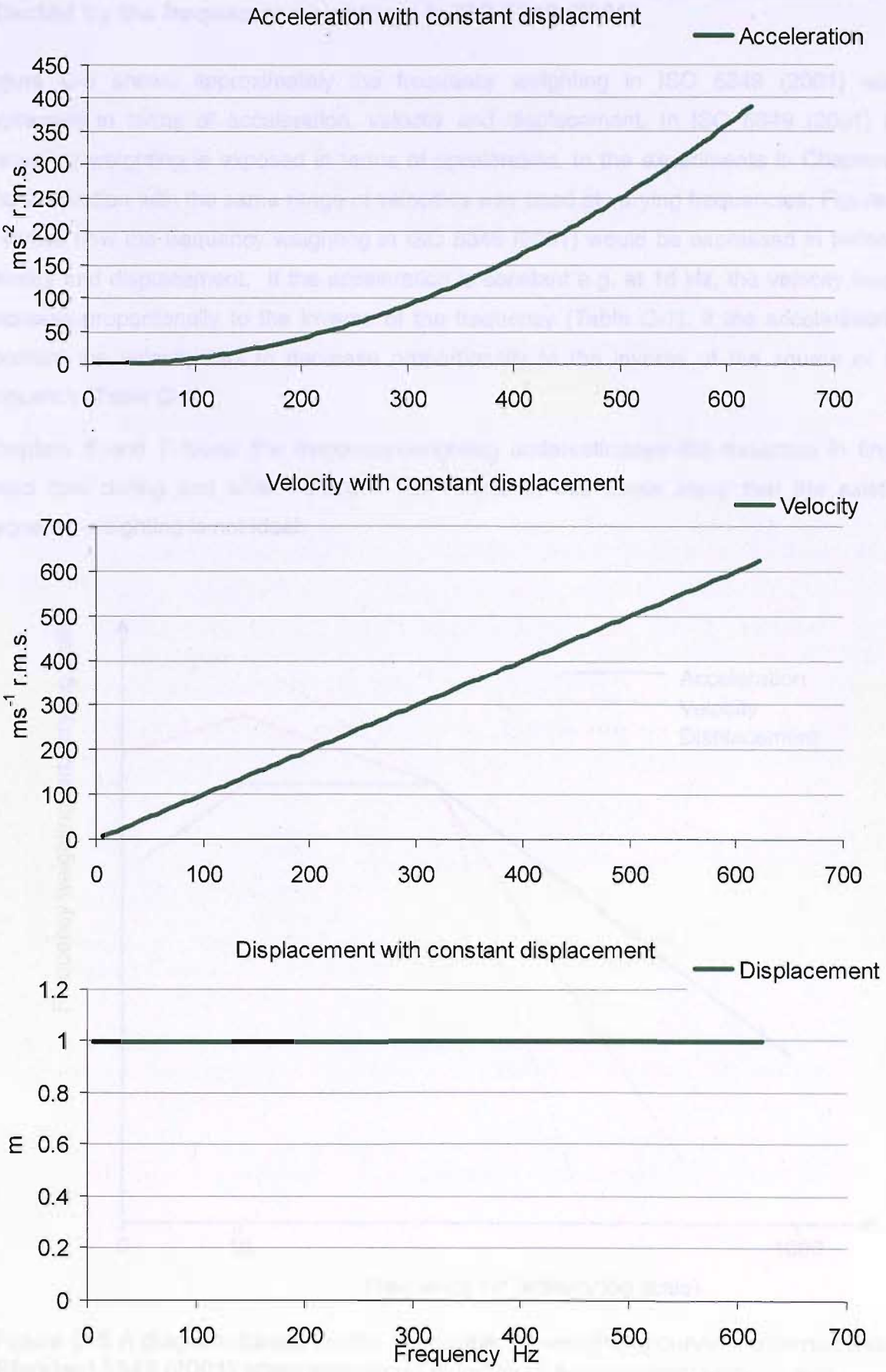


Figure C-4 Changes in acceleration and velocity with increasing displacement and varying frequency

C-2 How the relationships between displacement, velocity and acceleration are affected by the frequency weightings in ISO 5349 (2001)

Figure C-5 shows approximately the frequency weighting in ISO 5349 (2001) when expressed in terms of acceleration, velocity and displacement. In ISO 5349 (2001) the frequency weighting is exposed in terms of acceleration. In the experiments in Chapters 6 and 7 vibration with the same range of velocities was used at varying frequencies. Figure C-5 shows how the frequency weighting in ISO 5349 (2001) would be expressed in terms of velocity and displacement. If the acceleration is constant e.g. at 16 Hz, the velocity has to decrease proportionally to the inverse of the frequency (Table C-1). If the acceleration is constant the velocity has to decrease proportionally to the inverse of the square of the frequency (Table C-1).

Chapters 6 and 7 found the frequency-weighting underestimated the reduction in finger blood flow during and after vibration. The results in this thesis imply that the existing frequency-weighting is not ideal.

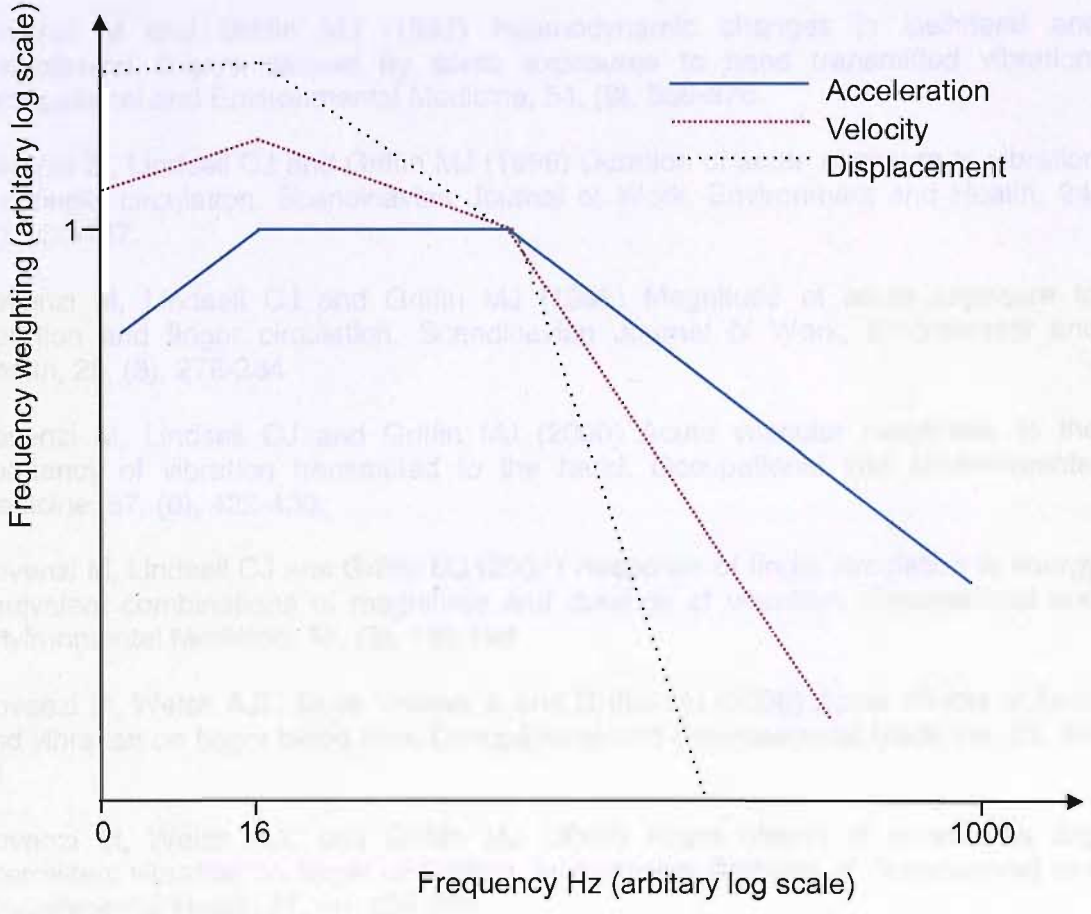


Figure C-5 A diagram based on the W_h frequency-weighting curve in International Standard 5349 (2001) when expressed in terms of acceleration, velocity and displacement

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