THE RESPIRATORY EFFECTS OF

WHOLE BODY VIBRATION IN MAN

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of Glasgow, in candidature for the
degree of Doctor of Medicine

by

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Abstract

Advances in military and civil aviation have given rise to the need for additional information on the human responses to low frequency structure borne vibration. The occupants of certain aircraft may be exposed to whole-body vibration at frequencies of less than 10 Hz and this is of interest in aviation medicine since vibrations of this type may excite human body resonances into large amplitude oscillations. The presence of vibration becomes of concern when it reaches such intensity as to disturb the aircraft itself and in particular where it represents a threat to comfort, health and efficiency of aircrew.

The work which is reported in this thesis concerns the respiratory effects of whole body structure borne vibration in man. In particular, two major areas have been studied - one concerning the effects of vibration on pulmonary ventilation and gaseous exchange, and the other, more specifically, on the effect of whole body vibration on metabolic oxygen consumption in man. The investigations were carried out at the Royal Air Force, Institute of Aviation Medicine, using a mechanical vibrator which applied sinusoidal vibration, at frequencies of 2 - 10 Hz and acceleration amplitudes of up to 1.4 Gz, to the buttocks of a seated subject.

The results of this study have shown that whole body vibration at certain frequencies and amplitudes can induce a marked increase in pulmonary ventilation, which is a true hyperventilation with hypocapnia. With exposure to vibration at high intensities, the magnitude of the hypocapnia was sufficient to produce symptoms in some of the experimental subjects. When the amplitude of displacement of the vibration was held constant the greatest

respiratory changes were found at the highest frequencies used in this study (6, 8 and 10 Hz). With this type of vibration, the frequencies and intensities which gave rise to the greatest degree of hyperventilation and hypocapnia were also those which caused the greatest degree of discomfort and pain in the thorax and abdomen of the vibrated subject. The onset of this pain and discomfort during exposure to constant amplitude vibration was advanced as a possible explanation for the observed respiratory changes. By contrast, exposure of the subject to vibration at a constant acceleration induced the greatest respiratory changes at the lower frequencies studied (2 and 4 Hz) and since these were not accompanied by pain or discomfort in the subject, labyrinthine stimulation was tentatively suggested as the causative mechanism.

The influence of a number of factors in modifying the respiratory changes associated with whole body vibration have been studied. It has been shown that firm restraint of the subject in the vibrating seat and the posture adopted by the subject during vibration had no effect on the hyperventilation and hypocapnia induced by vibration at various frequencies and intensities. Only by the application of firm external support to the thorax and abdomen of the vibrated subject (by means of a restrainer suit) were the respiratory changes during vibration eliminated or greatly reduced.

The practical importance of the finding of hyperventilation and hypocapnia in the subject exposed to whole body vibration have been discussed in terms of the in-flight hazard associated with this condition.

The investigations have also shown that whole body vibration causes a marked increase in oxygen consumption at certain frequencies and intensities. The results showed that this was not due to the muscular activity required by the subject to maintain posture in the face of vibration since changes of similar magnitude were found in conditions where the subject was restrained by harness in the vibrating seat and where he was unrestrained in the seat. High speed cinephotography revealed that during whole body vibration there was alternate tensing and relaxation of musculature - possibly as a protective mechanism - and it was believed that this phenomenon could explain the increased metabolic oxygen consumption observed during whole body vibration. The practical importance of the increased metabolic activity during vibration has been discussed in terms of the energy required by aircrew to fly various types of aircraft in a variety of conditions.

The findings of this investigation have advanced knowledge of the respiratory and metabolic responses of man to whole body structure borne vibration. The practical implications of the results of this study have been discussed in relation to the possible threat which they might pose to the comfort, safety and wellbeing of the pilot required to operate in conditions of in-flight vibration.

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CHAPTER 1

Introduction

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Introduction

1.1 Vibration and man

The twentieth century stands out as an age of remarkable technological progress, and dominant in man's achievements is the development of new and advanced forms of transportation systems. These systems extend from craft capable of lunar missions to those which now take to the depths of the oceans. Here on earth, less exotic but highly sophisticated vehicles transport man over the ground, on the water and through the air and whether ridden by a single man or by many, these vehicles pose serious problems in matching technological progress to the human being which this technology is intended to serve.

One such problem, which is common to all forms of transportation, concerns the vibrations which are imparted through the vehicle to the occupants, either as a function of the machinery which powers the vehicle, or the medium through which or over which it travels. Whenever mechanical work is done, some of the energy of the process, before being finally degraded into heat, may be dissipated as wave motions set up in the system wherein the work is done. The presence of mechanical vibration becomes of concern when it reaches such intensity as to disturb the machine itself, adjacent structures or human beings operating or using the equipment. Within the context of preventative medicine, vibrations are of interest in so far as they are a threat to comfort, health or efficiency of man. Vibrations disturbing man at work or in travel have many and varied sources; they may be experienced in and around propeller-driven aircraft, helicopters, air-cushion vehicles, rail transport and a wide variety of rotating and reciprocating machinery used in industry.

Of particular interest are the conditions which lead to whole-body vibration. In this case vibrations produced at source may be transmitted to a standing man through his feet, to a sitting man through his buttocks or to a reclining man through his entire posterior body surface. Other conditions in which vibrations are transmitted through selected parts of the body, occur for example, with the use of hand-held tools or certain types of vibrating machinery. A third type of exposure where the whole body or parts of it are immersed in a medium transmitting vibration occurs in connection with high intensity sound or blast exposure, infrasound exposure and the use of sonic cleaning devices.

Before discussing the physiological problems which may surround the imposition of whole-body vibration on man, it is first necessary to examine some of the sources and the nature of vibrations which can occur in transportation systems.

1.2 Sources of whole-body vibration in transportation systems

In the field of transportation there are many sources of vibration which may be transmitted through structures to the occupant of the vehicle. The disturbance which these structure-borne vibrations cause in man dependson the frequency, and amplitude of the vibration reaching the body and the length of time for which it is sustained. In modern forms of transportation, vibrations of widely varying frequencies may be produced and for the sake of convenience these are classified into those vibrations which are infrasonic and those which are within the range of human hearing (audible vibrations). Figure 1.1 shows some of the sources of vibration arising in various forms of transportation systems. Fortunately, structure-borne vibrations at frequencies much above 10Hz are poorly absorbed and well damped by the human body and so they are of interest mainly to design engineers rather than to the physiologist concerned with the comfort and safety of the occupants of the vehicle.

In the field of civil and military aviation the problem of whole-body structure-borne vibration may arise from a number of different sources and these will be discussed briefly in turn.

1.3 Sources of whole-body vibration in aviation

(a) Fixed wing aircraft

In conventional aircraft using either internal combustion or jet power, the presence of mechanical vibration which is disturbing to the crew and passengers is generally subsidiary to the problem of noise in the cabin. In certain types of aircraft, however, especially those with multiple piston engines, relatively low frequency components in the engine and propeller can give rise to troublesome structure-borne vibration at various crew stations. The frequency of this type of vibration lies approximately within the range 10 to 1000 Hz although at the intensities normally recorded during flight, these vibrations are not necessarily associated with specific physiological effects. Continuous heavy vibration at low sonic frequency may, however, add to the fatiguing effect of the internal acoustic sound field and may thus interfere with the ability of aircrew to carry out their in-flight tasks efficiently. A serious in-flight hazard may also arise from the vibration of instrument panels and transparencies. The sources and routes of transmission to the crew of aircraft vibration are many and varied. Vibrations generated by the passage of the aircraft through turbulent airspace, from the aircraft engines, from the jet efflux, or during the firing of aircraft mounted armament, may reach the aircrew through a number of routes. These include transmission of the vibration through airframe structures to the aircraft seat and subsequently to the torso, head and neck of the seated occupant. Alternatively, vibrations may reach the man through hand or feet operated controls, or through rigid and semi-rigid components of his personal equipment (e.g. delivery hose and oronasal facemask of the oxygen breathing equipment). In all these circumstances the vibrations transmitted from the source to

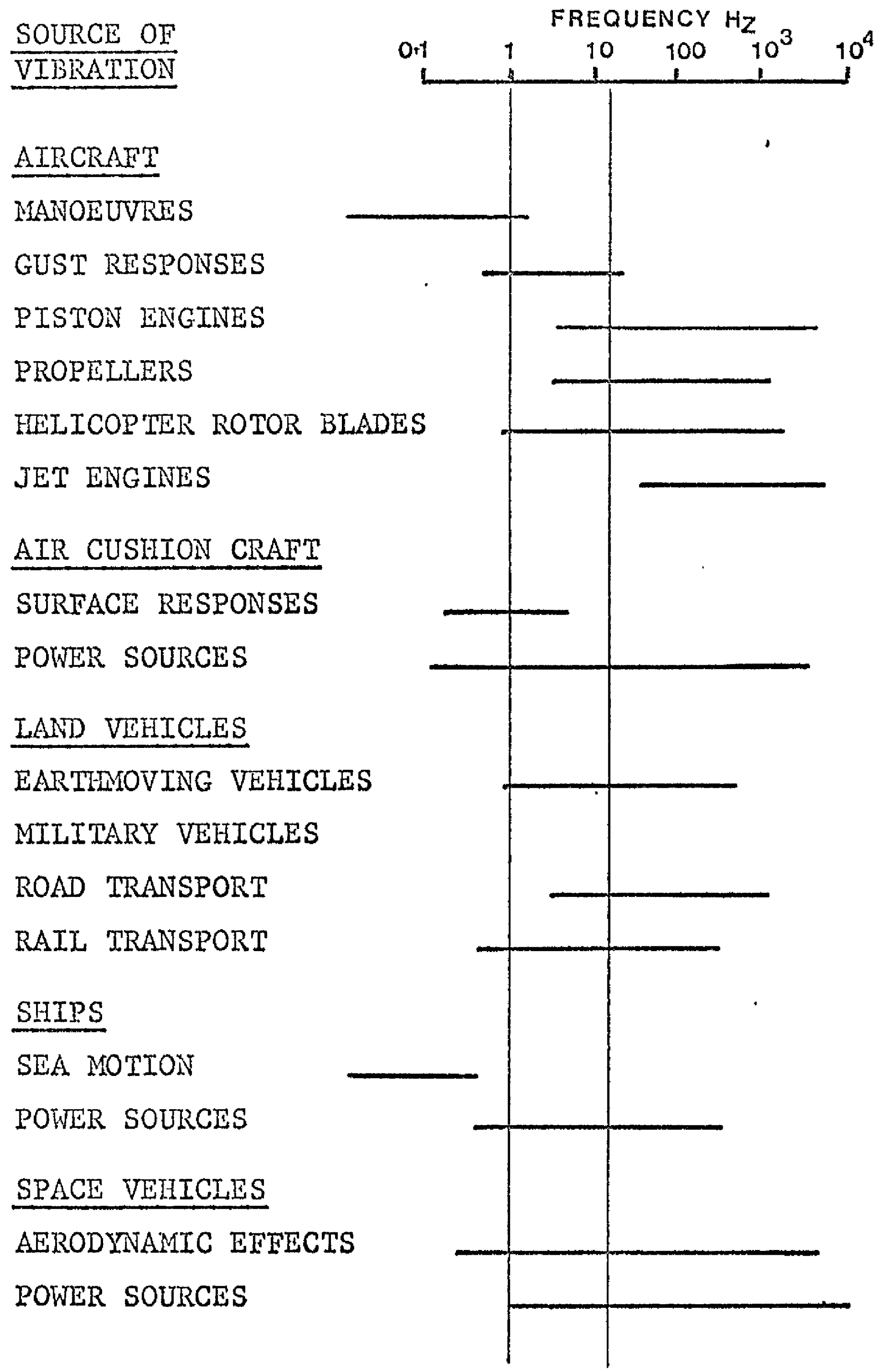

Figure 1.1 Some of the sources of vibration arising in various forms of transportation systems.

the man may be attenuated, altered or amplified depending on the specific characteristics of the aircraft, seating position of the occupant, etc.

(b) Rotary wing aircraft

Helicopters vibrate predominantly at frequencies related to the speed of the main rotor blades and in addition, harsh vibrations emanate from the engine, gearbox, transmission system and tail rotor blades. As in conventional fixed wing aircraft these sources are important in the generation of both internal and external sound fields, but in rotary wing aircraft heavy vibrations in the infra-sonic frequency range (below 10 Hz) and of quite considerable acceleration - amplitudes may be present as well. In some conditions of flight, vibration in helicopters may approximate fairly closely to simple harmonic motion (sinusoidal vibrations) while in other conditions of flight, recordings in more than one geometrical plane may reveal a composite motion containing both horizontal and vertical components of vibration. In aircraft of this type, low frequency structure-borne vibration is liable to occur and is of particular nuisance during transitional phases of flight (e.g. from hovering mode to straight and level flight). Under these conditions, vibration may seriously interfere with the task of the pilot, at a time when most exacting flying is demanded of him.

(c) Supersonic passenger transport aircraft

Recent developments in the field of civil transport aviation have brought problems of vibration in large passenger carrying aircraft designed to operate at high altitude and at speeds greater than that of sound. Because of their large size and supersonic configuration, such aircraft may have major modes of structural vibration at frequencies below 10 Hz, and the amplitudes of transient vibration may be considerable at the crew stations and in certain regions of passenger compartments. One special area of concern in aircraft of this type relates to the lack of damping of even moderate vibration disturbances by the rarified air at an altitude of 60,000 feet. Supersonic transport aircraft operating at such altitudes are unlikely to encounter severe turbulence but even mild vibration excited by a single gust may take the form of a poorly damped train of oscillations, at a frequency characteristic of the aircraft and taking several seconds to decay to imperceptibility. Oscillations of this type may at the least be disturbing to passengers, and at worst may induce physiological disturbances which could interfere with the efficiency of aircrew flying the aircraft. Structure borne vibration in the low frequency range may also be encountered during taxying of aircraft of this type.

(d) High speed, low level flight

Certain requirements in military aviation have given rise to the problem of low frequency structure-borne vibration. In order to avoid radar detection, many tactical and strategic missions of current military aircraft include the requirement for flight at altitudes of less than 150 feet at near sonic or supersonic speeds, and this brings with it the physiological stresses of noise, heat and vibration to the occupants of the aircraft. Since air is a viscous and resistive medium it offers considerable impedance to bodies moving through it at even moderate velocities. The resistive force on the moving aircraft rises steeply with increasing aircraft velocity and at subsonic speeds is related to the square of the indicated air speed. At speeds greater than 400 miles per hour, penetration of the atmosphere by an aircraft demands an enormous expenditure of power and under these conditions of flight there is a strong likelihood of power generated structure-borne vibration. In addition, at low altitudes thermal and ground atmospheric turbulence is present more or less continuously, depending for its magnitude upon the pressure, temperature and velocity of the air. Passage of an aircraft through areas of intense atmospheric turbulence may seriously disturb the flight path due to random bumps of low frequency, large amplitude and irregular wave form. The vibration disturbance to the occupant of the aircraft flying in these conditions is proportional to the indicated air speed, and at high speed flight at low level, the bumps are encountered more frequently and more abruptly. The vertical components of the vibration are generally considered to be the most disturbing, but during high-speed flight through turbulence, aircraft can indulge in unpleasant pitching and yawing movements in addition to purely vertical oscillation. The quasi-random jostling to which the crew are subjected may make the task of the pilot and navigator extremely difficult and tiring under these circumstances.

(e) Firing of weapons

When powerful weapons, such as machine guns or cannon are fired from fixed wing or rotary wing aircraft, a periodic series of impacts is transmitted to the airframe through the gun mountings. The quality and intensity of the vibration imposed by weapon firing depends largely upon the length of the burst of gunfire, and the relationship between the rate of firing and the resonant frequencies of the responding structures. Structural vibration can also be excited by the expanding gases from gun muzzles impinging upon nearby surfaces of the aircraft.

1.4 Characteristics of vibration exposure

Vibration is conveniently defined as the condition in which a body undergoes a series of reversals of velocity (Crede, 1957). This definition, although it does not embrace all conceivable conditions of vibration, serves as a reminder that several factors must be considered in any dynamic system. Velocity implies displacement in finite time and the reversal or change of velocity involves acceleration and its derivatives. The displacement and its derivatives may be translational or angular, as in torsional vibration; they may be free as in a swing pendulum, or forced, in which the disturbance is maintained by an external fluctuating force. In the field of aviation medicine, one is normally concerned with sustained forcing vibrations and Guignard (1960) suggested a more restricted definition of vibration relating to human physiology, to the effect that vibration is a sustained, structure-borne disturbance applying a translatory movement to the body and perceived by the senses other than hearing.

(a) Regular or periodic vibration

The vibration from any particular source has a characteristic quality which depends upon the frequency composition of the wave-form. The simplest possible vibration is a steady to and fro movement, like a pendulum or a tuning fork emitting a pure tone. In simple harmonic motion (SHM) of this type, the shape of the displacement/time graph is termed sinusoidal, since the motion can be treated as the projection on the diameter of the locus of a point moving round a circle with constant angular velocity. An example of sinusoidal vibration of this type is shown in figure 1.2. The nature of the vibration is defined by its frequency and its amplitude. The frequency is the number of complete cycles of motion per second (Hz) and the amplitude is the extent of the motion from the mid or equilibrium position (the larger the amplitude the more intense is the vibration). In physiological studies of the effects of vibration on man, sinusoidal vibration is usually applied to the subject and it is customary to use acceleration-amplitude as a measure of the intensity of the vibration rather than displacement amplitude. The acceleration-amplitude of a sinusoidal vibration (in G) is obtained from the displacement (in inches) by the formula:

$$\text{acceleration} = \frac{4\ \pi^2\ f^2 A}{386}$$

where : G = force exerted by gravity

A = displacement (inch)

f = frequency (Hz)

and 386 is the International Standard Acceleration (inch-pound-second scale)

In aviation, pure sinusoidal vibration is rarely encountered, although something approaching it may occur at very low frequencies in aircraft, under the influence of hunting in automatic flight control systems. More frequently occurring in aircraft is a steady state periodic vibration approximating to simple harmonic motion but often containing several harmonics. Vibration of this type, known as complex harmonic motion, cannot be defined in such simple terms as the sinusoidal wave and in determining its source and assessing its importance it is necessary to analyse it into simple components. This type of vibration may be regarded as the sum of a number of sine-wave vibrations going on simultaneously each having its own amplitude, frequency and phase angle. If the vibration is fairly complex, it is helpful in visualising the results of analyses to plot the amplitude of each Fourier component against a scale of frequency - the so called frequency 'spectrum'. Figure 1.2 shows examples of simple harmonic (sinusoidal vibration) and complex harmonic vibration with their appropriate 'spectra'. It may be seen that the spectrum for a pure sine-wave consists of a single line whose position marks the frequency and whose height indicates the displacement amplitude. The complex harmonic vibration shown in the illustration has two spectrum lines but in more complex examples may have multiple spectrum lines.

(b) Irregular or aperiodic vibration

Quite commonly, a vibration wave-form recorded in flight will appear to be completely irregular and will contain no recognisable periodicity. It is then said to be aperiodic. This type of vibration is encountered in aircraft flying through meteorological turbulence in which the airframe is continually shaken by masses of moving air, or gusts whose local velocity, momentum and time of incidence have a random distribution. The harmonic content of vibrations of this type is great and inconstant and unlike a sinusoidal wave cannot be described by a simple equation of motion. In practice, the nature of such vibrations is best assessed using methods of spectrum analysis. In figure 1.2 an example of

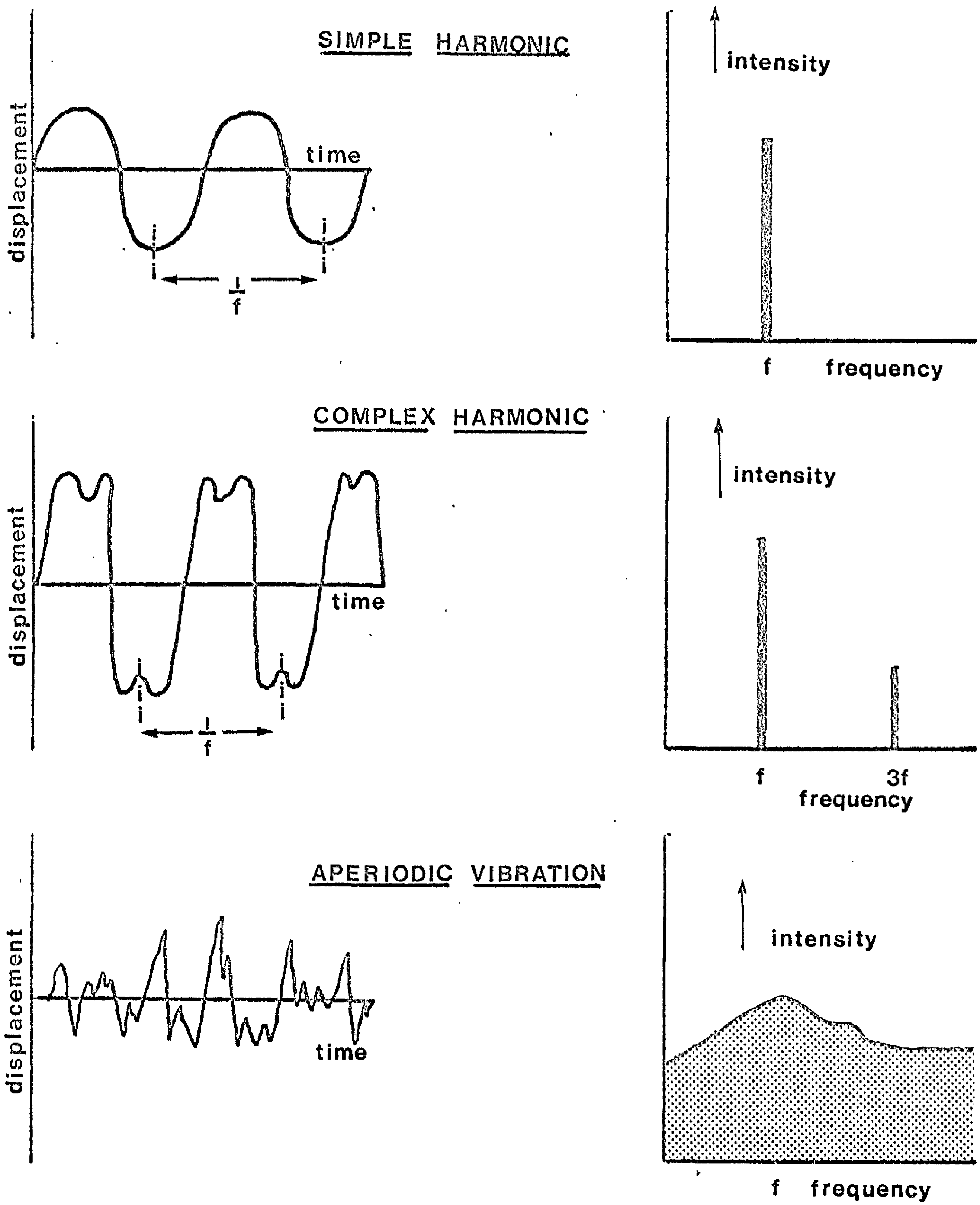

Figure 1.2 Examples of various types of vibration with their frequency 'spectra'.

aperiodic vibration is shown together with the appropriate spectrum. In a truly random vibration the representation of all frequencies would be equal over a finite time but in many real cases (as in the example shown in figure 1.2) representation is maximal in the region of one specific frequency. The main interest in random, aperiodic vibration of this type lies in the ability of the fundamental and harmonic wave motions to excite parts of the body to resonate at their inherent natural frequencies. A more detailed discussion on body resonance phenomena in relation to the effects of whole-body vibration in man will be given in a later chapter of this thesis.

(c) Directional modes of whole-body vibration

Whole body vibration can have three linear and three rotational degrees of freedom. Linear vibrations are characterised by the three axes of a rectangular coordinate system and the terminology commonly used in physiology relates the coordinate system to the human skeleton. Thus, acceleration vibration in the longitudinal (head to foot) axis is designated by G_z, acceleration in the fore and aft (chest to back) axis by G_x and acceleration in the lateral axis by G_y. Rotational accelerations around a centre of rotation are separated into pitch (rotation about the y axis), roll (rotation about the x axis) and yaw (rotation about the z axis). These modes of vibration are illustrated in figure 1.3.

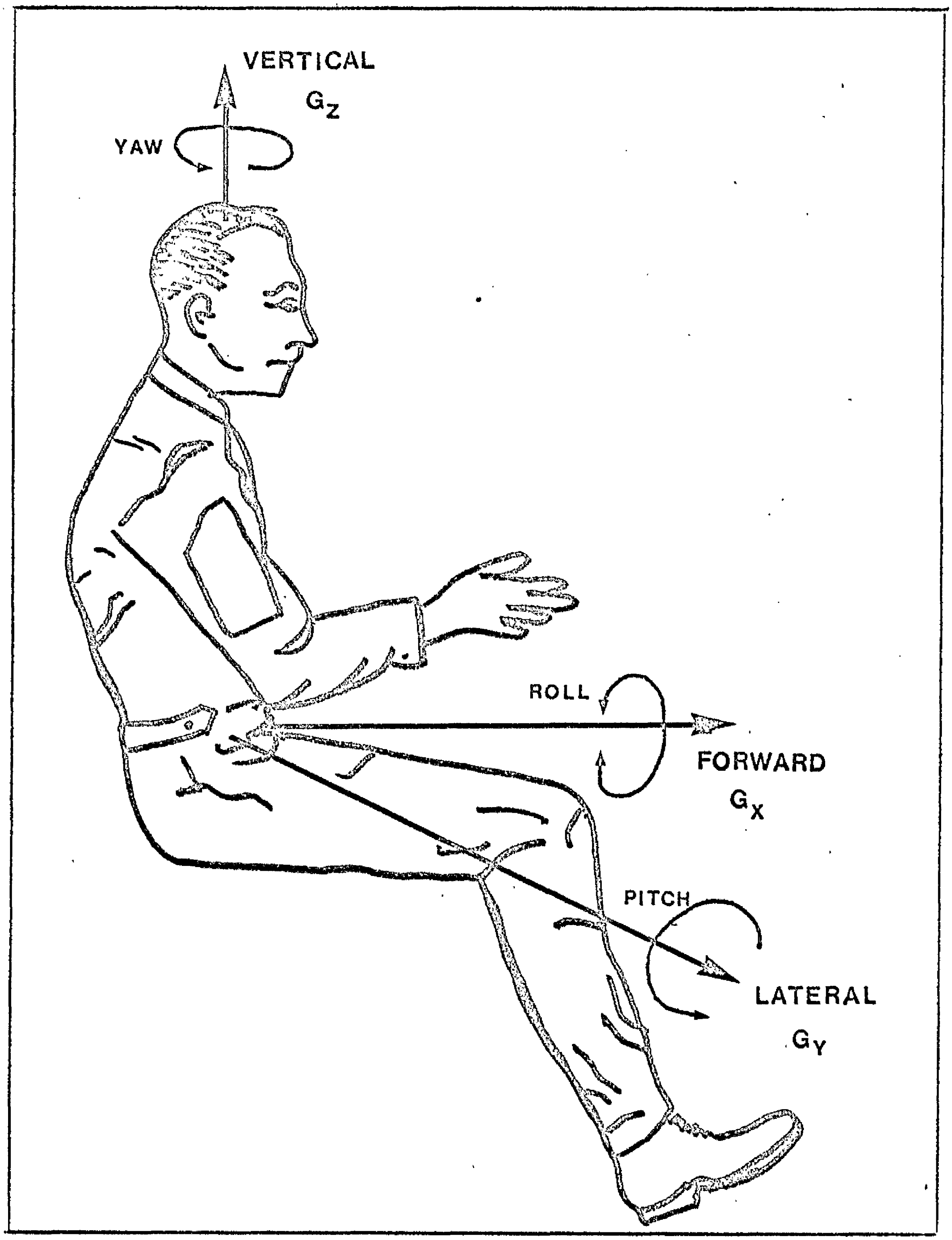

Figure 1.3 The linear and rotational modes of whole body vibration.

(d) Nature of vibration used in experimental studies

It has been shown in previous paragraphs that structure borne vibration is a problem associated with many different forms of transport systems and in the present context is frequently encountered in both civil and military aviation. It has also been noted that the characteristic of vibrations which occur in aviation may be of extremely complex wave form and may reach the occupant of the aircraft from a number of directions and by various routes. In studying the response of the human subject to vibration of the type encountered in aircraft, two complementary approaches are generally adopted. The first is by observation of subjective reaction or alteration of a task performance under conditions of vibration as they actually occur in flight. Such in-flight studies are expensive, occasionally hazardous, and may place restrictions on the design of experiments and recording of physiological data and are in addition, very difficult to repeat. This approach is therefore often supplemented by the use of large vibrating machines (gust-simulators) which reproduce in the laboratory some components of the real vibratory motion. The second approach is to examine human response to experimental steady-state sinusoidal vibration, applied in one axis of the body using a variety of sine-wave generators for the purpose. This latter approach is the one often used by aviation physiologists as a first step in vibration studies since it has the advantage that the stimulus can be conveniently produced, measured, repeated and defined in simple numerical terms of frequency and amplitude. In the experiments on whole body vibration which have been carried out in this investigation, and which form the basis of this thesis, the experimental vibration has been applied to the buttocks of the seated subject by means of a hard platform oscillated in the vertical plane by an electric motor. The physiological responses of the subject to whole-body vibration which are reported in this thesis refer, therefore, only to pure sinusoidal vibrations of varying frequencies and amplitudes which have been applied to the body in one direction only (vertical, Gz).

1.5 Human response to whole body vibration

Previous studies relating to the human responses to vibration cover the physiological and pathological effects of structure-borne vibration as well as subjective reactions, comfort and performance and the results of many of these investigations have been reviewed in detail by Guignard (1965). The physiological mechanisms underlying many of the effects of whole-body vibration have not yet been established with any certainty and are at present the subject of active study.

In the field of aviation medicine, there is considerable interest in the physiological effects of low frequency structure-borne whole-body vibration due to the emphasis on high speed low-level flight as a tactical requirement in military aviation. In previous paragraphs it has been stated that flight at high speed and low level, particularly in conditions of meteorological turbulence, may induce accelerations in the aircraft which resemble mechanical noise with superimposed quasi-steady state vibration due to airframe structural response. To the physiologist, vibrations produced in aircraft flying in these conditions are of particular interest since they present with frequencies below about 15 Hz at which both human body resonances and major aircraft modes are excited into large amplitude oscillations. Mechanical vibration at higher frequencies can occur in these circumstances and may produce physiological disturbance to the occupant of the aircraft but in the main they are well attenuated by the body itself and by the adoption of simple protective measures by aircrew. Vibrations at these higher frequencies occurring in flight are of less concern, therefore, than the more commonly produced low frequency structure-borne variety.

There have been comparatively few studies on the physiological disturbances brought about by structure-borne vibration in the low or infrasonic frequency range, although it is known that they may affect man in a variety of different ways. These disturbances include effects on the respiratory system, interference with speech, effects on the control of posture, blurring of vision, interference with performance of a psychomotor task and body injury due to jolting. A number of these physiological disturbances due to whole-body vibration and the range of frequencies at which the disturbances are produced is given diagrammatically in figure 1.4. In the field of aviation medicine, interest is directed primarily towards these disturbances due to whole body vibration which may impair the ability of aircrew to carry out their in-flight tasks with efficiency. The diagram shown in figure 1.5 summarises some of the ways in which disturbance due to whole-body vibration may adversely affect the performance of aircrew. It should be noted that the effects of vibration on the occupant of the aircraft may be compounded with other stresses which are liable to be encountered during high speed low-level flight, for example, acceleration, noise, heat and excessive work load.

A detailed study of the literature, has revealed that there is a particular lack of information concerning the effects of whole-body vibration on the human respiratory system. Early German research before and during the Second World War suggested that whole-body vibration could induce manifestations of alarm with increases in respiratory rate, pulmonary ventilation and metabolic oxygen consumption (Müller, 1939; Cörmann, 1940; Loeckle, 1940). The increases in metabolic oxygen uptake during whole-body vibration at infrasonic frequencies have been studied both in man (Duffner, Hamilton & Schmitz, 1962; Dixon, Stewart, Mills, Varvis & Bates, 1961; Ernsting, 1961), and in animals (Carter, Largent & Ashe, 1961),

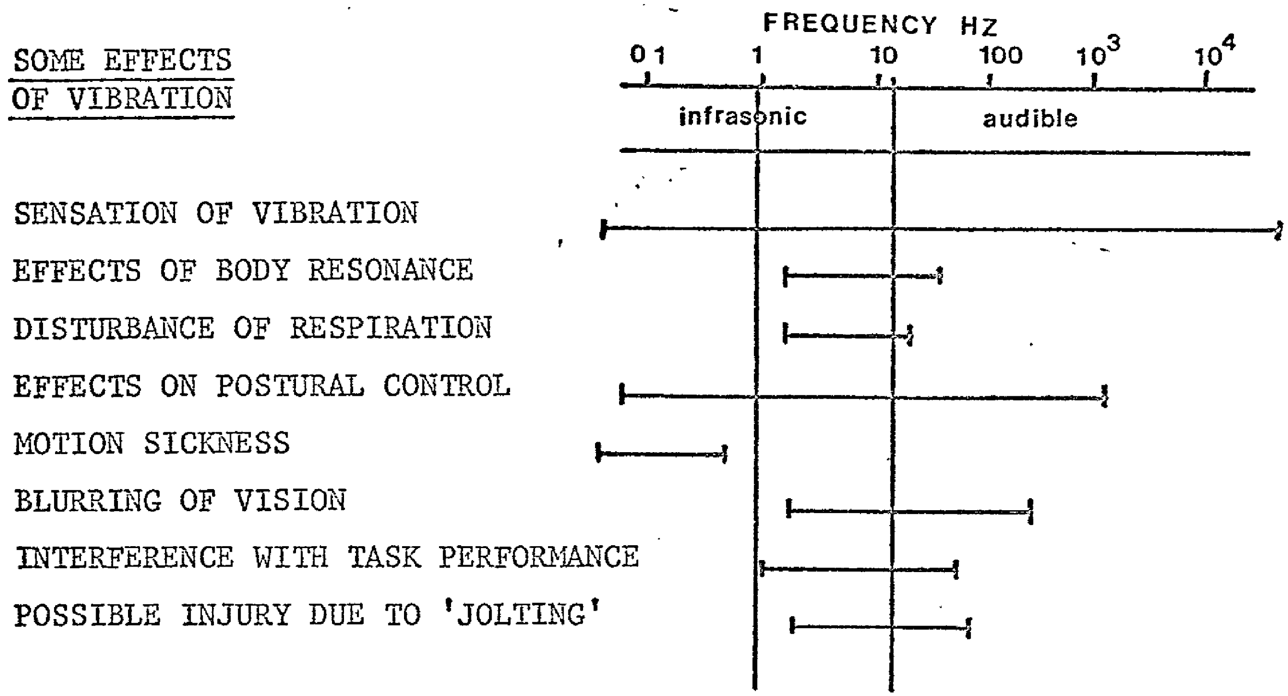

Figure 1.4 A number of the physiological disturbances induced by whole body vibration.

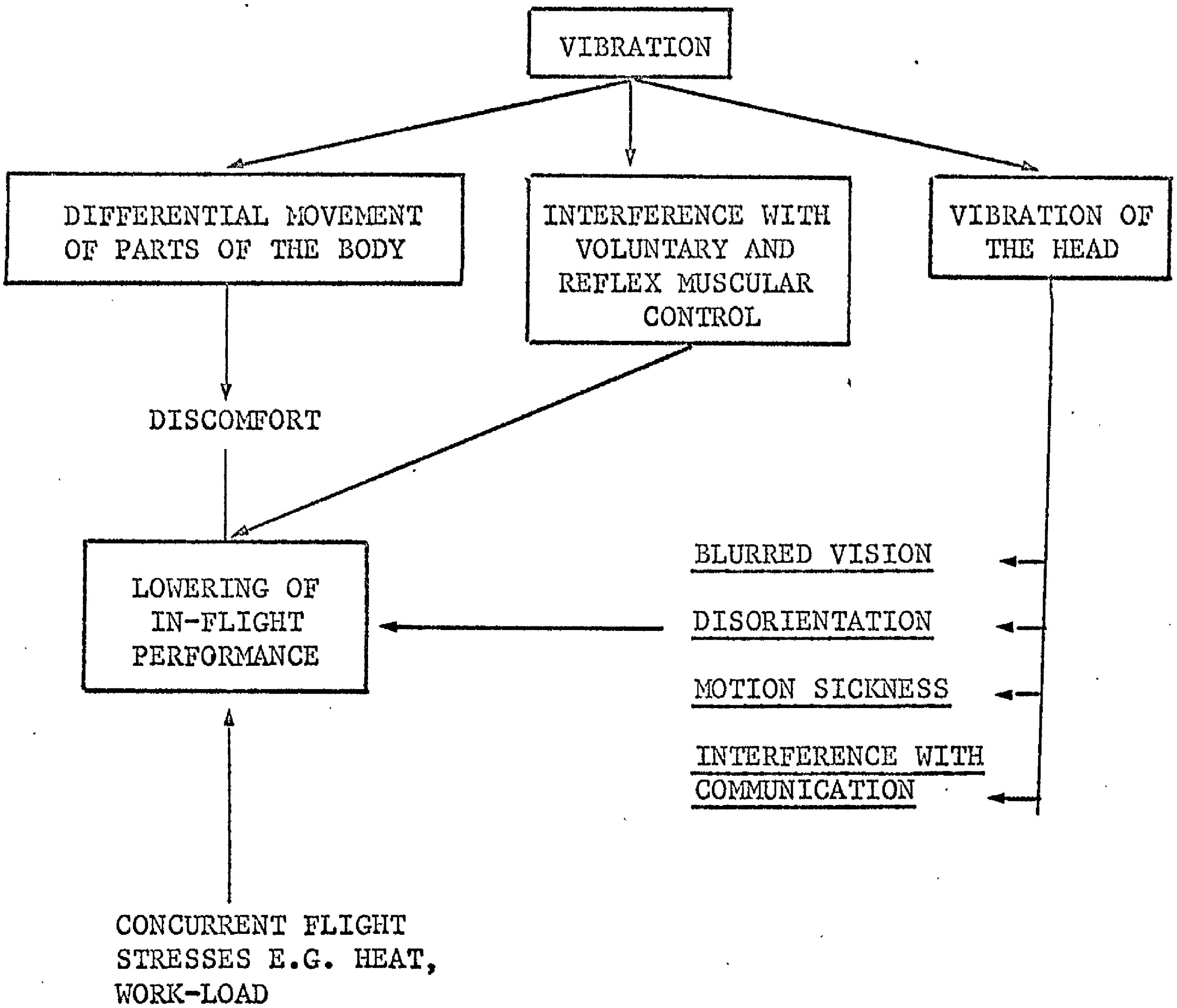

Figure 1.5 Diagram of some of the ways in which whole body vibration may affect the performance of aircrew.

and in most cases these have been related to the intensity of the applied vibration. The same groups of workers have also measured pulmonary ventilation in the human subject exposed to whole-body vibration and have observed a marked increase in ventilation volume, during the applied vibratory stimulus. One of the most important respiratory effects noted by several investigators is that of hyperventilation induced by whole-body vibration at low frequencies with, in some cases, marked symptoms of hypocapnia (Ernsting, 1961; Hornick, 1961; Dixon et al, 1961 and Duffner et al, 1962). Certain other respiratory variables, including vital capacity (Duffner et al, 1962) and pulmonary compliance (Ernsting, 1961) have been measured during and following low frequency vibration applied to the whole body.

In aviation medicine, the respiratory effects of whole-body, low frequency vibration are not only of academic interest but are of extreme practical importance in the comfort, well-being and safety of aircrew operating in stressful conditions of high speed, low-level flight. Thus, a knowledge of metabolic oxygen consumption and the related metabolic heat output of the subject during all conditions of flight is essential to the design and development of aircraft and personal thermal conditioning systems, which are required to maintain aircrew in thermal comfort particularly in conditions of high speed flight. Similarly, it is desirable to have a knowledge of the level of pulmonary ventilation in aircrew during various flight conditions and to be able to define the conditions of vibration in flight (e.g. during high speed flight in turbulence) which can induce hyper-ventilation and hypocapnia in the subject with the attendant threat to flight safety.

It was considered, therefore, that it would be of great practical value to carry out investigations into the effects of whole-body vibration in the low frequency range (2 - 10 Hz) and to measure the metabolic oxygen consumption, gaseous exchange and pulmonary ventilation in man under these conditions. In the succeeding chapters of this thesis the results of these experiments are reported and discussed in relation to their significance in aviation medicine.

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CHAPTER 2

Review of the literature

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In the introductory chapter attention was drawn to the fact that advances in aviation have given rise to the need for additional information on the human responses to low frequency structure-borne vibration. It was stated that very few studies have been carried out on the effects of low frequency vibration on the human respiratory system and that, in particular, there is a paucity of information on the effects of vibration on pulmonary ventilation and metabolic oxygen consumption in man.

An examination of the literature relating to the human responses to low frequency whole-body vibration has shown that previous investigators have been concerned with mechanical resonance effects arising in the body in response to the vibratory stimulus. The reports of previous authors point to the siggificance of such body resonance in the human responses to low frequency vibration which include discomfort, degradation of performance and a number of physiological effects of varying specifity. There is now strong evidence to support the belief that many of these physiological disturbances in man arise directly or indirectly as a result of differential movement or deformation of particular body structures as they resonate at a characteristic frequency during exposure of the subject to whole body vibration. In view of thepast and recent interest in this aspect of the human response to vibration, the first part of this review of the literature deals with previous investigations which have been carried out in the field of body resonance phenomena.

The second part of the review deals with the work of previous authors on the respiratory effects of whole body vibration in man with particular emphasis on the effects of vibration on pulmonary ventilation, gaseous exchange and metabolic oxygen consumption. These aspects of whole body vibration form the bulk of the experimental investigations reported and discussed in this thesis.

It has been stated previously that aircrew flying certain types of fixed wing and rotary wing aircraft are particularly liable to encounter low frequency structure borne vibration and this may cause an increase in metabolic energy expenditure at a time when the work load may be already high. In order to assess the practical importance of this physiological response, examination has been made of the literature relating to the energy expended by aircrew flying various types of aircraft. For convenience, this review is included in the last part of this chapter.

2.1 Body resonance phenomena

Resonance effects in the human body as a response to vibration at low frequencies were first noted by German workers before the Second World War. They observed that on excitation along the spinal axis, the human body possesses a dominant mode of vibration in the frequency range 4 to 6 Hz which could be elicited either by steady-state sinusoidal vibration (Müller, 1939) or by vertical impact (Waas, 1935). Prior to these investigations, Reiher and Meister (1931) had carried out a study of the thresholds of tolerance to low frequency vibration in a large number of subjects and had observed that exposure to vibration at frequencies around 5 and 10 Hz was associated with particular discomfort. Although these workers made no comment on the significance of this observation, it is now clear that this effect was most likely due to a resonance phenomenon. In early studies on the human response to whole-body vibration, von Békésy (1939) reported that he could find no effects which could be attributed to resonance at frequencies of vibration below about 3 Hz, while Cörmann (1940) who studied the mechanical response to low frequency whole-body vibration in a large number of subjects found no resonance characteristics at frequencies above 15 Hz. In later investigations, Goldman (1948) measured the tolerance of human subjects to low frequency vibration and noted that there was a pronounced reduction in the threshold of subjective tolerance with applied vibrations in the frequency range 4 to 5 Hz. This effect he attributed to resonance of various parts of the body. Loeckle (1950) observed a vertical mode of human body vibration in the frequency range 6 to 10 Hz which he attributed to resonance of the abdominal viscera in general and to resonance of the liver mass in particular. In later studies, the belief that resonance effects of the thoraco-abdominal system may play a major role in the human response to low frequency vibration was strengthened by observations by Latham (1957) who described severe upper abdominal pain elicited by vibration at a frequency of 8 Hz and by Magid, Coermann & Ziegenruecker (1960) who noted chest discomfort in their subjects exposed to whole-body vibration at frequencies between 5 and 9 Hz.

Although a number of workers have reported effects due to body resonance which have arisen in the course of studies into various aspects of the human responses to low frequency whole-body vibration, there have been comparatively few investigations aimed specifically at defining the frequencies of vibration which will illicit these resonance phenomena. In the main, two techniques have been used by independent groups of workers to carry out more detailed and specific analysis of body resonance. These techniques involve measurement either of the transmissibility of the applied vibration through the body, or the measurement of the mechanical impedance characteristics of the body in response to vibration. With each of these techniques, it is possible to observe and measure the response of parts of the body to vibration at various frequencies and acceleration-amplitudes applied to the whole body and to define the characteristic of the vibratory stimulus which will set up resonance in any particular structure of the body. The majority of investigators who have studied resonance effects in the body in response to vibration have utilised the first of the two alternative experimental techniques - measurement of t transmissibility. Transmissibility is defined as the ratio of the vibration amplitude measured at the part of the body under consideration to the amplitude of the forcing vibration. If the motion of the part concerned is equal in amplitude to the forcing frequency, resonance of the part is absent, and transmissibility is unity. In conditions of resonance, however, the ratio is greater than unity since the input vibration is amplified in the structure concerned. In practice a number of workers have measured the transmissibility of vibration and observed the occurrence of resonance by means of accelerometers attached to the part of the body under investigation (Dieckmann, 1957; Guignard, 1959; Latham, 1957; Roman et al, 1959). Other workers have studied resonance in body structures by measurement of transmissibility using cinematographic techniques (Guignard & Irving, 1959; Roman et al, 1959) and specifically in the abdominal viscera by means of radiography (Loeckle, 1944). Measurement of transmissibility has also been used to study resonance effects in the thoraco-abdominal system in man by Du Bois, Brody, Lewis & Burgess (1956) and in animals by Brody, Connolly & Wander (1959) who observed the response to sinusoidally varying air pressures applied to the trachea.

An alternative approach to the measurement of body resonance has been used by a few investigators in this field. The technique used by these workers has been the measurement of the mechanical impedance characteristics of the body in response to applied vibration. Mechanical impedance is defined as the complex ratio of the power transmitted to a vibrated system to the vibrational velocity of excitation. If values of mechanical impedance of whole or part of the body are plotted graphically against vibration frequency, resonance of a body structure at any particular frequency is observed as a localised maximum value in the curve. This technique has been used more extensively in studies of resonance effects in the skull and other parts of the human skeleton which are excited by vibrations in the higher frequency range 1600 to 1800 Hz. It has, however, been applied to investigations of resonance phenomena during whole-body vibration at infrasonic frequencies (Dieckmann, 1957; Coermann, Ziegenruecker, Wittwer & von Gierke, 1960).

The results obtained by various workers in the field of body resonance phenomena point to the fact that there are certainly two and possibly three major modes of resonance in the human body. There is general agreement amongst investigators that the first mode of body resonance occurs at a vibration frequency of about 4 to 5 Hz. Although the existence of this mode of body resonance is now firmly established, the anatomical basis for the phenomenon is less well understood. Using a technique of transmissibility measurement supplemented by high speed cinematography, Guignard &

Irving (1959) concluded that the first mode of body resonance at frequencies of about 4 to 5 Hz was due largely to resonance of the upper torso and shoulder girdle. In their work, a graphical plot of measured transmissibility against the frequency of the applied vibration showed a maximum value at 5 Hz which was more prominent when recorded at the shoulder than at the head. In a later investigation Coermann et al (1960) showed, however, that resonance at the shoulder girdle alone was not sufficient to explain the first mode of whole-body resonance. Using a technique whereby the mechanical impedance of the body was measured these workers demonstrated a resonance of the thoraco-abdominal system at a frequency of about 4 Hz. This observation was later confirmed by the work of Ernsting (1961) in which intra-abdominal pressure was measured in the seated subject during whole-body low frequency vibration. It is clear from these studies that no simple anatomical explanation can be given for the first mode of whole-body resonance at 4 to 5 Hz but it is possible that this response is dictated by at least two resonating systems - the pectoral girdle and thoraco-abdominal viscera.

Several groups of investigators have described a second mode of resonance in the body during applied longitudinal vibration. This second mode of resonance which occurs in the frequency range 11 to 14 Hz was first observed by von Békésy (1939) and later by Dieckman (1957), Magid et al (1960) and Coermann (1962). These workers observed maximum values in their impedance curves at frequencies between 11 and 14 Hz during whole-body vibration studies in man. Goldman (1957) has suggested that this second mode of resonance may be associated with axial compression of the body between the trunk and head during whole-body vibration, although as yet, no satisfactory explanation for this phenomenon is possible. A third resonance occurring in the human body at frequencies of vibration between 17 and 25 Hz has been described by Dieckman (1957) and Latham (1957) and this may be due to resonance of the head on the trunk with possible axial compression of the curvical spine.

Although the main interest in body resonance phenomena has been directed towards vibration in the longitudinal (vertical) direction there have been a few studies on the effects of vibration applied to the human body in more than one plane. Thus it has been shown that when the seated subject is vibrated by a fore-and-aft or sideways movement of the seat, a shearing force is applied to the buttocks. A low frequency resonance occurs due to flexion of the lumbo-dorsal spine, and, in fore-and-aft vibration, articulation at the hip joints. Von Békésy (1939) recorded a lateral bending mode at 1.6 Hz and more recently, maximum values in horizontal seat-to-head transmissibility have been reported in the range 1.5 to 2.5 Hz (Dieckmann, 1958; Hornick, Boettcher & Simons, 1961). It is now believed that resonance near 2 Hz is the dominant mode in horizontal vibration of the seated man. The importance of the human response to vibration applied simultaneously in more than one axis has been pointed out by Grant (1961). He showed that in the composite vibration of helicopters the direction and magnitude of the resultant acceleration are important in determining its subjective acceptability. Thus, if a subject is exposed to simultaneous vertical and horizontal (fore-and-aft) vibrations of equal frequency and amplitude, a circular motion of the seat may be produced by suitable phasing of two vibrations, and it has been demonstrated that depending on the direction of circular motion the subjective responses will be characteristic of those due to either vertical or horizontal excitation. In practice, and of importance in the present context, a coupled mode related to the transverse resonance characteristics of the torso can be excited at a frequency of 2 Hz applied to the body in a vertical direction. Begbie, Gainford, Mansfield, Stirling & Walsh (1963) have recorded vertical vibrations of 3 to 4 Hz and lateral oscillations of 0.5 to 1.5 Hz at the head in railway passengers, the dominant resonant system to the body presumably having amplified particular components of the forcing vibration of the train. It is believed that similar phenomena may occur in aviation.

Of considerable interest to the physiologist are the physical factors, apart from frequency itself, which determine the appearance of any particular body resonance. Guignard (1965) has classified these factors into those which are intrinsic, like body build, posture and muscular tension, and those which are extrinsic, like the direction, intensity and site of application of vibration to the body, the distribution, weight and stiffness of clothing and equipment carried on the person and dynamic interactions between the body and the structure through which vibration is applied. Thus, Guignard & Irving (1960) found that tensing the pectoral musculature modified the resonance at a frequency of 5 Hz, which occurred with whole-body vibration and had the effect of increasing both the stiffness and damping of the system. Edwards (1950) and Coermann (1962) showed that changes in posture could markedly influence the transmission of vibration through the body. Among the extrinsic factors which modify resonance in the body, one of the most important is the direction of application of vibration, and certainly the intensity or force of the applied vibration has a marked effect. Thus, Coermann (1962) found that the transmissibility of the body at resonant frequencies was reduced at acceleration-amplitudes greater than about 0.5 G, an effect attributed (Guignard & Irving, 1960) to involuntary muscular tensing. A similar reduction of the seat-to-head transmissibility with increasing forced acceleration from 0.2 to 0.4 G was reported by Hornick et al (1961). Other extrinsic factors like stiffening of the body by means of bindings or semi-rigid flying clothing may modify the response to whole-body vibration by augmenting body resonance (Coermann, 1962). It is clear from a review of the literature relating to the human response to whole-body vibration, that many investigators have failed to appreciate the significance of intrinsic and extrinsic factors which can modify body resonance effects and in turn the physiological response to the forcing vibration.

In the present context, great interest surrounds the resonance characteristics of the human chest-lung and abdominal system since this may play a major part in the respiratory effects of whole-body low frequency vibration. In a previous paragraph it was stated that Coermann et al (1960) using mechanical impedance methods demonstrated resonance of the human thoraco-abdominal system at a frequency of about 4 Hz. It was also stated that a similar observation had been reported by Ernsting (1961) during experiments in which seated subjects were exposed to whole-body vibrations at infrasonic frequencies. This latter author measured the intra-abdominal pressure during whole-body vibration and noted that maximum amplitude of oscillation occurred at frequencies of vibration between 3 and 5 Hz. In their studies, Du Bois, Brody, Lewis & Burgess (1956) connected a small sinusoidal pump with a constant stroke volume directly to a mouthpiece placed between the lips of a relaxed subject. They determined the relationship between the mouth pressure and gas flow into and out of the mouth at various pump frequencies and recorded movements of the chest wall and abdomen. The overall pressure and flow changes thus measured were in phase at a frequency of 5.8 Hz indicating at least one resonance of the chest-lung system at this frequency. Using similar methods in animals it has been shown that in the dog, the natural resonant frequency of the chest-lung system is 5.4 Hz (Hull & Long, 1961) and in the cat 9 - 10 Hz (Brody, Du Bois, Nissell & Engleberg, 1956). In an extension of these animal studies Brodie, Connolly & Wander (1959) examined the contribution made by various viscera to the resonant frequency of the overall thoraco-abdominal system in the cat. By surgical removal of various viscera they demonstrated that the abdominal wall and the liver exert a major influence on the resonant characteristics of the whole system. Using radiographic techniques, Nickerson & Coermann (1962) showed that in the dog the abdominal viscera and thorax resonate as a single mass at a frequency of between 3 and 5 Hz.

Using a variety of electrical analogue devices Shephard (1966) and Clements, Sharp, Johnson & Elam (1959) investigated the parts played by various components of the respiratory system in the overall resonance behaviour of the chest-lung system. Both groups of workers demonstrated that the upper respiratory tract plays a major role in this respect. Using a more complex electrical analogue model to simulate parallel branches in the respiratory bronchial tree, Van den Berg (1960) showed that various components of the respiratory tract have their own characteristic resonant frequency and suggested that the resonant frequency of the whole respiratory system may be compounded from the interaction of resonance properties in the individual components.

Although the exact resonance behaviour of the human chest-lung system is not yet clear, it is now believed that resonance phenomena may be responsible for some of the respiratory effects of low-frequency whole-body vibration. Indeed, Coermann et al (1960) describe the thoraco-abdominal system as one of the most important systems affecting the resonant properties of the human body and the physiological responses of the subject to low frequency whole-body vibration.

2.2 Respiratory effects of whole-body vibration

(a) Pulmonary ventilation

There have been very few studies on the respiratory effects of low frequency whole-body vibration. Early German workers (Müller, 1939; Cörmann, 1940 and Loeckle 1940) reported that subjects exposed to vibration showed an increase in respiratory rate, pulmonary ventilation and metabolic oxygen consumption. These respiratory effects were attributed to a raised metabolic activity due to muscular effort on the part of the subject in order to maintain his posture in the face of the vibratory stimulus.

This explanation was re-inforced by the finding that the increases in the respiratory indices were much greater when the subjects were standing up, than when they were seated during low frequency vibration.

The idea that passive movement of the body, particularly of the limbs might stimulate pulmonary ventilation was first introduced by Geppert & Zuntz (1888) and later restudied by Bahnson, Horvath & Comroe (1949). These latter authors showed that passive movement of the legs on motor-driven pedals was accompanied by a marked increase in metabolic oxygen consumption and a corresponding increase in pulmonary ventilation. In a later study, Dixon, Stewart, Mills, Varvis and Bates (1961) investigated the respiratory effects of passive movement of the body using a commercially made domestic exercising machine which applied rhythmical movements at frequencies of 0.5 to 0.8 Hz to the buttocks, arms and legs of the seated subject. They showed that certain types of passive movement of the body caused a balanced increase both in pulmonary ventilation and metabolic oxygen consumption in the experimental subjects, while certain other types of movement caused an increase in pulmonary ventilation which was in excess of the metabolic requirements of the body. The passive vibratory movement which caused hyperventilation (and in a few subjects symptoms of hypocapnia) was that applied to the buttocks of the subject in a nearly vertical mode, although it was found that passive flexion and extension of the arms and to and fro movement of the upper torso could augment the observed respiratory effects. The authors were unable to explain the mechanism of production of hyperventilation and hypocapnia during near-vertical whole-body vibration although they considered it possible that labyrinthine reflexes might be involved. They also believed that this mechanism might explain the hyperventilation in pilots flying at high speed and low level through turbulence, previously reported by Balke, Wells & Clark (1957).

In the course of experiments to determine the transmission of vibration through the human body at frequencies between 1.7 and 9.5 Hz, Guignard & Irving (1960) noted that some of their subjects complained of lightheadedness, peripheral paraesthesia and other symptoms of hypocapnia which suggested that the form of whole-body vibration used in their experiments might induce hyperventilation. Since at that time, advances in military aviation required the occupants of certain aircraft to fly at high speed and low altitudes it was feared that exposure to structure-borne vibration at frequencies of less than 10 Hz under these circumstances might induce dangerous hyperventilation and hypocapnia in aircrew. In order to investigate this problem, therefore, Ernsting (1961) examined the respiratory effects of vertical sinusoidal vibration applied to the buttocks of a seated subject over the frequency range 1.7 to 9.5 Hz and at acceleration amplitudes of up to $\pm$ 1G. He demonstrated in his study that there was a significant increase in pulmonary ventilation at forcing accelerations which exceeded 0.5 G at a frequency of 9.5 Hz. A disproportionately large increase in pulmonary ventilation when related to the increase in oxygen uptake, together with an increase in the respiratory exchange ratio was adduced as evidence of hyperventilation. In some of his subjects Ernsting also recorded an arterial carbon dioxide partial pressure of less than 25 mm Hg after only 2 minutes of vibration at about 1G acceleration-amplitude and at a frequency of 9.5 Hz. These subjects reported marked symptoms of hypocapnia. In seeking a cause for the hyperventilation found during low frequency vibration in these experiments, Ernsting examined the possibility that a contributory factor might be the superimposition of oscillations upon the respiratory flow at the forcing frequency. He pointed out, however, that the magnitude of the passive mechanical effect (which was greatest at 3 - 4 Hz) was considerably smaller, in terms of volume reciprocation, than the anatomical dead-space and he considered that the contribution by these oscillations to the production of hyperventilation would be minor, except perhaps at whole-body resonance. Ernsting did note, however, that vibration which was sufficiently severe to cause a significant increase in pulmonary ventilation at the higher range of frequencies studied, also caused discomfort in his subjects and he believed that the observed hyperventilation might be explained by the stress of physical discomfort added to the metabolic demands of postural muscle activity during whole-body vibration. Paradoxically, it was found that during vibration at a constant acceleration-amplitude of $\pm$ 0.25 G, the increase in pulmonary ventilation was greatest at the lowest frequency studied (1.7 Hz). This frequency is below that of any known mechanical resonance of the respiratory system, and vibration exposure was not associated with any discomfort on the part of the experimental subject. The changes in pulmonary ventilation which occurred during vibration of this type was, therefore, tentatively attributed to labyrinthine stimulation - an explanation which was also advanced by Dixon et al (1961) for the hyperventilation and hypocapnia observed during their whole-body vibration studies.

In an attempt to define some of the human responses to whole-body vibration of the type likely to be encountered in aviation, Duffner, Hamilton & Schmitz (1962) carried out an investigation into the respiratory effects of low frequency vibration. They exposed their subjects to vibration at constant acceleration-amplitudes of $\pm$ 0.15 and $\pm$ 0.35 G and frequencies of 2 to 7 Hz for a period of about four minutes. They observed a marked increase in pulmonary ventilation at the start of vibration at all frequencies, which gradually returned towards resting levels near the end of the vibration period. The changes in ventilation which occurred at an acceleration-amplitude of $\pm$ 0.35 G were greater than those which occurred at an acceleration-amplitude of $\pm$ 0.15 G and quite marked hyperventilation was found at frequencies of vibration of 4 - 5 Hz. Since the longitudinal resonant frequency of the human body lies in this range, the authors suggested that oscillation of the thoraco-abdominal viscera with stimulation of deformation receptors including those in lung tissue, might be responsible for initiating a reflex hyperventilation during whole-body vibration.

Hoover & Ashe (1962) pointed out that previous workers had studied the respiratory effects of whole-body vibration in man during relatively short term exposures lasting 3 to 5 minutes. They investigated the effects of vibration at acceleration-amplitudes from $\pm$ 0.3 to $\pm$ 2.9 G over the frequency range 2 to 15 Hz with exposures lasting twenty minutes, and found a very marked increase in pulmonary ventilation at forcing frequencies of 6, 8, 11 and 15 Hz. In their study the increase in pulmonary ventilation at these frequencies of vibration was brought about almost entirely by an increase in tidal volume. Although no measurements were made of end-tidal or arterial carbon dioxide partial pressures, the authors believed that the increased pulmonary ventilation at the higher range of vibration frequencies studied was true hyperventilation since on cessation of the vibration stimulus values of minute volume ventilation, respiratory rate and tidal volume fell to below those obtained during the period of rest prior to vibration - a phenomenon which is often seen during recovery from experimental hyperventilation. No explanation, however, was offered by the authors for the respiratory changes observed during the vibration period.

There is now strong evidence that whole-body vibration at certain acceleration-amplitudes and frequencies can cause a marked increase in pulmonary ventilation and, in some cases, hyperventilation and hypocapnia. The exact mechanism causing the hyperventilation is, however, less clear. Lamb & Tenney (1966) carried out a series of experiments in order to try and elucidate the mechanisms involved in the production of hyperventilation during whole-body vibration. They studied the effects of vibration applied to supine subjects by means of motor-driven foot pedals. The frequency of the applied vibration in their experiments was 6.6 Hz and the acceleration-amplitude of the vibration as measured by means of accelerometers applied to the thorax, was $\pm$ 0.9 G. The ventilatory response of the subject exposed to the vibratory stimulus was rapid in onset, highly reproducible and persistent. By the first or second breath after the start of vibration tidal volume and respiratory frequency increased and the end-tidal carbon dioxide partial pressure began to fall, reaching a new steady value within about 60 - 120 seconds. By the end of a six minute period of vibration the end-tidal partial pressure of carbon dioxide had fallen by as much as 13 mm Hg in some of the experimental subjects, indicating that the vibration had induced a severe degree of hyperventilation and hypocapnia. The authors noted that there was a direct relationship between the magnitude of the applied vibratory stimulus and the magnitude of the ventilatory response.

In an attempt to discover the mechanism involved in the production of hyperventilation during whole-body vibration Lamb & Tenney carried out an additional series of experiments. In this study vibration was applied directly to the lower limbs of the subject but failed to excite hyperventilation although there was an increase in minute volume ventilation which was proportional to the slight increase in metabolic oxygen consumption. When vibration (at a frequency of 6 Hz) was applied to the abdomen alone, by means of cyclical inflation of the bladder of a standard United States Air Force antigravity suit no hyperventilation was seen. This evidence, together with the fact that rigid abdominal binders applied to the thorax and abdomen failed to reduce the ventilatory response during the whole-body vibration experiments, led the authors to suppose that the respiratory responses could not be mediated through specific mechanoreceptors sited in the abdominal and thoracic viscera. In order to test an alternative possibility that stimulation of the semicircular canals during whole-body vibration might be responsible for the observed respiratory changes, Lamb and Tenney applied local anterior-posterior vibration movements directly onto the head (which was encased in an American football type protective helmet). With locally applied vibrations of this type (at a frequency of 6 Hz) they were able to reproduce a range of nodding head movements similar to those observed during their whole-body vibration experiments. In spite of vigorous head movement at this frequency of vibration there was, however, no hyperventilation observed in the experimental subject and the authors concluded that stimulation of the semicircular canals could not be the prime cause of the hyperventilation seen during whole-body vibration. As in previous studies, the work of Lamb & Tenney (1966) failed to demonstrate a specific anatomical site for the reception of the stimulus to ventilation during whole-body vibration. Their experiments, however, confirmed the marked hyperventilation and hypocapnia found during whole-body vibration at certain frequencies and accelerations-amplitudes and the authors suggested that this ventilatory response somehow depended upon the whole experience of vibration applied to the body.

Although very little is known about the causative mechanism, the significance of hyperventilation during whole-body vibration lies in its effect upon performance and in its possible synergism with other forms of environmental stress in aviation. Part of the work reported in this thesis, therefore, has been carried out in order to define the nature and magnitude of the respiratory changes which occur with the application of whole-body vibration and also to provide additional information in this field which might contribute to the safety, comfort and wellbeing of aircrew exposed to low frequency structure-borne vibration in flight.

(b) Metabolic oxygen consumption

In the introductory chapter attention was drawn to the paucity of information concerning metabolic oxygen consumption in the subject exposed to whole-body low frequency vibration. It was stated that such knowledge is essential to the design of aircraft and personal thermal conditioning systems for aircrew operating in conditions of high speed, low level flight through turbulence where thermal stress is already a problem.

In early investigations into the respiratory effects of whole-body vibration, German workers noted that there was an increase in metabolic oxygen consumption which they believed was due to the added muscular effort required to maintain posture in the face of the vibratory stimulus. The magnitude of the increase in metabolic oxygen consumption and the nature of the vibratory stimulus causing the effect was not, however, clearly defined in these early reports (Müller, 1939; Cörmann, 1940 and Loeckle, 1940). In his work on the respiratory effects of low frequency whole-body vibration, Ernsting (1961) measured the metabolic oxygen consumption and carbon dioxide output in the subject exposed to vibration for periods of up to five minutes. He observed that there was a significant increase in metabolic oxygen consumption when the forcing frequency of vibration was 9.5 Hz and the acceleration-amplitude was greater than $\pm$ 0.5 G. The metabolic oxygen uptake of the subject increased from a mean value of 0.346 L(NTP)/min at rest to a value of 0.557 L(NTP)/min during the period of whole-body vibration. The author suggested that this increase in metabolic oxygen consumption might be due to the increased muscular work required to maintain posture during the violent shaking which occurred in these circumstances. A similar explanation for an increase in metabolic oxygen consumption was advanced by Duffner, Hamilton & Schmitz (1962) who observed this phenomenon during exposure of their subjects to whole-body vibration at frequencies of 2 - 7 Hz and at two levels of peak acceleration-amplitude ($\pm$ 0.15 and $\pm$ 0.35 G). These workers observed that the greatest increase in metabolic oxygen consumption occurred with vibration at the lower frequencies in the range studied and at the higher level of intensity ($\pm$ 0.35 G). They believed that the increase in metabolic oxygen consumption occurred at the lower frequencies of vibration rather than at frequencies causing body resonance phenomena since large vertical displacement of the vibration platform was required at low frequencies and considerable physical exertion was required on the part of the subject in order to maintain his posture.

Gaeuman, Hoover & Ashe (1962) exposed human subject to whole-body vibration at frequencies of 2, 6, 8, 11 and 15 Hz with peak acceleration-amplitudes of $\pm$ 0.05, $\pm$ 0.46, $\pm$ 0.82, $\pm$ 1.55 and $\pm$ 2.88 G respectively. The data obtained in their experiments showed that there was a positive linear correlation of metabolic oxygen consumption in the subject with respect to increasing frequency of vibration. In these studies, the subjects sat on a simple seat attached to the vibrating platform, no form of body restraint was used and the subject was free to assume the most comfortable posture during the vibration. The authors offered two possible explanations for the increased metabolic oxygen consumption obtained at the higher frequencies studied. In the first case they agreed with some previous workers that the muscular effort involved in attempting to maintain posture was one possible explanation for the observed phenomenon. As a second explanation, they offered the possibility that metabolic oxygen uptake increased as a result of voluntary or involuntary tensing of muscle masses during vibration as an attempt by the body to dampen the vibration and thereby reduce transmission to more vulnerable parts. While the cause of the increased metabolic oxygen consumption during low frequency vibration could not be explained in precise terms, the authors pointed out that the increase in muscular activity (either to maintain posture or as a protective dampening measure) was of sufficient magnitude as to be a contributor to fatigue over extended periods of vibration. This observation is of significant practical importance in the field of aviation where low frequency structure-borne vibration may be encountered in the aircraft over long periods.

From the data obtained in their studies, Hood, Murray, Urschel, Bowers & Clark (1966) concluded that an increase in muscular activity was responsible for the large increase (+ 76%) in the metabolic oxygen consumption which they obtained with supine subjects exposed to whole-body vibration at a frequency of 10 Hz and an acceleration-amplitude of $\pm$ 1.2 G. Since their subjects were fully restrained and in a supine position, little or no effort was required on the part of the subject to maintain posture and the authors believed that reflex muscular contraction occurred during vibration possibly as a result of stimulation of muscle spindles, in various situations in the body. In their investigations they compared the metabolic oxygen consumption obtained in man during exposure to vibration at a frequency of 10 Hz and an acceleration-amplitude of $\pm$ 1.2 G with that obtained during exposure of an anaesthetised dog to vibration at a frequency of 10 Hz and an acceleration-amplitude of $\pm$ 1.3 G. In both experiments there was a large increase in metabolic oxygen consumption during the period of exposure to vibration (in man, the increase was 76%, and in the anaesthetised dog, the increase was 83%). The authors concluded from this experiment that muscular tension due to anxiety could be ruled out as the prime causative factor in the increased metabolic oxygen consumption observed during the period of vibration.

It is clear from a review of the scant literature relating to the metabolic oxygen consumption of subjects exposed to whole-body low frequency vibration, that more information is required in this field. In particular a more precise knowledge of the magnitude of the increase in metabolic oxygen consumption is required for human subjects exposed to vibrations of various frequencies and acceleration-amplitudes. In addition, more information is required in order to allow an explanation of the cause of the increase in metabolic activity which occurs during whole-body vibration. Part of the work reported in the thesis is concerned therefore with measurement of metabolic oxygen consumption during exposure of the subject to various conditions of experimental low frequency whole-body vibration together with an investigation of the possible mechanisms which may be responsible for the phenomenon. The results of studies carried out in this area are reported in the succeeding chapters of this thesis.

2.3 Energy expended by aircrew flying various types of aircraft

It has been pointed out in a previous paragraph that exposure of the human subject to whole body vibration at certain frequencies may induce an increase in metabolic activity. It has also been stated that whole body structure borne vibration is liable to be encountered in certain types of fixed wing and rotary wing aircraft during conditions of flight in which the occupant of the aircraft may be already exposed to a heavy work load. There is considerable interest, therefore, in knowing the metabolic energy expended by the pilot at the controls of aircraft of this type during normal vibration - free flight. Although there is much information regarding the energy costs of performing a wide range of human activities (Passmore and Durnin, 1955) very few studies have been carried out on the energy expended by aircrew during flight - mainly due to the technical difficulties imposed by the accommodation of measuring equipment in the confined space of an aircraft cabin. Some of the most detailed reports on the energy expended by aircrew relate to the piloting of simple propeller driven light and medium weight aircraft (Corey, 1948; Littell & Joy, 1969; Billings, Foley & Huie, 1964), while others relate to the energy required by aircrew to fly multi-engined heavy weight aircraft in routine emergency and combat situations (Lovelace, Carlson & Wulff, 1944; Hitchcock, 1950; Kaufman, Callin & Harris, 1970). In the present context, however, the data gained from these studies are of limited interest since they refer to the energy costs of flying aircraft in which in-flight structure borne vibration is unlikely to reach sufficient magnitude as to induce serious physiological disturbance in the pilot. There have been very few reports on the metabolic energy expended by aircrew flying fixed wing aircraft of the type in which whole body structure-borne vibration may be encountered and until recently there has been a paucity of information regarding the energy requirements of the pilot flying rotary wing aircraft. In this part of the chapter, therefore, the previous studies which have been carried out on the energy expended by aircrew flying these two categories of aircraft are reviewed in turn.

High Performance Combat/Training Aircraft

There are very few reports in the literature relating to the energy expended by aircrew flying high performance aircraft. In an early study, Penrod (1942) reported values of pulmonary ventilation in pilots flying World War II, US fighter type aircraft. Using these limited data, Kaufman et al (1970) attempted to estimate the energy expended by the aircrew operating in routine and in combat flight. In their analysis, a number of assumptions were made in the calculations of energy expended, with regard to the breathing patterns of the aircrew, the mean body surface area, the caloric equivalent of oxygen and respiratory exchange ratio. The result of this analysis shows that aircrew of World War II fighter type aircraft during routine flight expended little more energy than they did during resting conditions (mean value estimated for rest and routine flight = 46kcal/m^2hr). During combat situations, however, certain complex attack or defensive aerobatic manoeuvres, caused a mean increase in energy expenditure to an estimated value of 65 kcal/m^2hr.

Recognising the difficulty of applying the conventional techniques of measuring energy expenditure within the confined space of a single seat high performance aircraft, Tiller, Greider & Grabiak (1957) used a standard laboratory open-circuit technique to measure the metabolic oxygen consumptions of aircrew during a variety of simulated flight conditions in a F9F-5 aircraft simulator. The study involved nine experienced aircrew four of whom had active combat experience. Metabolic oxygen consumption of the aircrew subjects was measured at rest, during simulated routine flight, during combat aerobatic and in certain in-flight emergency situations. The results of this study showed that routine 'flight' in the F9F-5 simulator caused a small increase in the mean value of energy expended by the pilot at rest (mean resting value = 50 kcal/m^2hr) to a mean value of 59 kcal/m^2hr during the flight profile. The physical activity required to correct a simulated emergency situation caused a further increase in energy expenditure (mean value during the emergency phase = 73 kcal/m^2hr). The highest value of energy expended by aircrew occurred during the simulated combat attack/defensive manoeuvre and reached a mean value of 78 kcal/m^2hr. Although there is no information available concerning the relationship between the physical forces required to operate the controls of the F9F-5 simulator as compared with the actual aircraft controls it is believed that the sophistication of the simulator was such as to make these results of energy expenditure reasonably representative of values expected for aircrew flying the aircraft itself in various manoeuvres.

The only study of the energy expended by the pilot flying a modern high performance aircraft is that reported by Lorentzen (1965). In his investigation, five experienced pilots flew a T33 jet training aircraft in various in-flight manoeuvres at altitudes ranging from 4,000 to 10,000 ft. Metabolic oxygen consumption was measured using an 'open circuit' technique with the pilot at rest, during routine level flight and during the in-flight manoeuvres. The aerobatic manoeuvre used in this study was designed to place a work load upon the pilot similar to that which would be required during a combat situation. The results of this study indicate that the values of energy expenditure obtained with the pilot flying the T33 jet trainer aircraft in routine flight were the same as those obtained with him at rest (mean value at rest and during routine flight = 46 kcal/m^2hr). During short-term intensive aerobatic manoeuvres (similar to those which would be executed under conditions of combat) the mean value of energy expenditure was reported as 97 kcal/m hr. This latter value is considerably higher than the estimated values of energy expenditure in pilots flying World War II fighter aircraft in actual combat conditions. The validity of the values of energy expenditure of pilots during combat aerobatics in Lorentzen's study is, however, highly doubtful since measurements were obtained only over a very short period of activity, the in-flight manoeuvre was not repeated in exactly the same manner on each occasion and considerable difficulty was experienced in obtaining accurate measurements of pulmonary ventilation due to outboard leaks from the oronasal facemask.

The mean values of energy expenditure reported by various authors for aircrew flying high performance aircraft during a variety of in-flight conditions are summarised in Table 2.1.

Table 2.1 Mean values and range of energy expended by aircrew flying high performance combat/training aircraft

Source	Type of Aircraft	Number of Subjects	Mean values and range of energy expended by aircrew (kcal/m^2hr) during: Rest	Routine flight	Emergency or combat flight
Penrod (1942)	World War II fighter	8	46*	46*	65*
Tiller et al (1967)	F-9F-5 (simulator)	9	50 (47-53)	59 (50-62)	78 (74-84)
Lorentzen (1965)	T-33 jet trainer	5	46 (36-51)	51 (45-58)	97 (84-122)

* Values estimated by Kaufman et al (1970) from data originally reported as pulmonary ventilation.

Rotary Wing Aircraft

Littell & Joy (1969) measured the energy expended by twelve experienced pilots flying three types of US Army helicopters. The aircraft used in this study consisted of a single rotor, light-weight (2,163 lb) OH-6A helicopter; a medium weight (9,500 lb) single rotor utility UH-1D helicopter and a heavy-weight (33,000 lb) tandem rotor CH-47A helicopter. Energy expenditure was measured with each pilot seated at rest and during routine flight at an altitude of 500 ft, and in close proximity to the ground (take-off, hovering, etc.). Although the three aircraft used in this study differed greatly in mechanical complexity (ranging from the simple OH-6A to the highly complex CH-47A) the authors found no significant difference in the energy expended by the pilots flying each type of helicopter for each phase of flight. The mean values of energy expended by aircrew flying the three aircraft in various situations are given in detail in Table 2.2. In general, however, it was observed that the energy required to fly the aircraft close to the ground (hover, ascend) was very much greater than that required for routine flight at an altitude of 500 ft. During routine flight at altitude, the energy expended by aircrew was not increased beyond that expended with the pilot seated at rest (mean values for three aircraft with pilots at rest and during routine flight were both 50 kcal/m^2hr). The energy expended by aircrew during the ascent phase and hovering close to the ground was 59 kcal/m^2hr and

61 kcal/m^2hr respectively. The results obtained by Littell & Joy indicate that hovering rotary wing aircraft requires a high level of physical activity on the part of the pilot to maintain precise control and stability of a dynamically unstable aircraft.

Billings, Bason & Gerke (1970) used an 'open circuit' technique to measure the energy expended by the pilot flying two types of helicpter, the Hiller UH-12E and the UH-12EL. The latter aircraft differed from the former only in that it had a pilot-assist hydraulic boost system on the cyclic and collective pitch controls and therefore presumably required less physical effort on the part of the pilot during flight. These authors pointed out that in the study by Littell & Joy (1969) the helicopters which they had used were sophisticated turbine powered vehicles whereas there were in service a number of the older reciprocating engine models which lacked many of the control refinements found in newer aircraft. Using the older UH-12E series helicopters, Billings et al (1970) measured the energy expended by the pilot first at rest and then during pre-flight run-up, take-off and routine level flight with a subsequent approach and landing. Measurements were repeated during a period of 7 - 9 minutes of hovering, manoeuvres close to the ground and also during a period of 10 minutes during which the aircraft was flown at cruising speed at an altitude of 500 ft. The results of this study show that the energy expended by aircrew flying the two types of helicopter (UH-12E and UH-12EL) in various situations was not significantly different. Billings et al (1970) confirmed the finding of Littell & Joy (1969) that hovering and operation of the aircraft close to the ground demanded considerably more physical effort and energy expenditure on the part of the pilot as compared with that required for cruise and routine flight at altitude. The values of energy expended by aircrew flying in the UH-12E series helicopters were considerably higher for all phases of flight as compared with values obtained by Littell & Joy. During cruise at altitude the mean energy expended by the pilots was 73 kcal/m^{2}hr and during hovering and operation close to the ground was 85 kcal/m^{2}hr. The authors concluded that the higher energy cost obtained with the UH-12E series aircraft in all phases of flight, was probably due to the lack of sophisticated control systems (e.g. lack of auto-throttle and full control boost). The investigation suggests that powered controls in helicopters do spare the pilot a significant degree of energy expenditure.

Kaufman, Callin & Harris (1970) measured the energy expended by aircrew flying a heavy duty (21,000 lb) twin gas turbine engined, J-CH3 helicopter, in routine flight and during a simulated emergency procedure. The emergency situation used in this study consisted of the pilot hovering the aircraft close to the ground with all pilot-assist devices inoperative. It was found in this study that cruise flight at altitude demanded the least energy expenditure on the part of the pilot as compared with the emergency situation (hovering with all pilot-assist systems inoperative), where the energy expended by the pilot increased from a mean value of 50 $kcal/m^2hr$ during routine flight to a mean value of 69.5 $kcal/m^2hr$ in the emergency.

Mean values of the energy expended by aircrew flying a variety of types of rotary wing aircraft are summarised in Table 2.2.

Although there are only a few reports relating to the energy cost of flying high performance fixed wing and rotary wing aircraft, this part of the review of the literature indicates that the total flight profile of the aircraft may be considered as a number of different phases (e.g. ascent, routine flight, emergency situation etc.), all of which place differing demands on the pilot in terms of physical activity and energy expenditure. The reports of previous authors show that the energy required to fly a high performance fixed wing aircraft in normal routine flight requires little energy in excess of that expended by the pilot seated at rest. During other in-flight activities, however, which require more active and precise control of the aircraft (e.g. instrument approach, landing and in-flight manoeuvres), or during active combat flying more physical exertion is demanded of the pilot and his energy expenditure is high. It is also during these periods of high physical exertion that structure borne vibration may be encountered in the aircraft and there is evidence that this may well cause additional metabolic activity in the pilot. The practical importance and the magnitude of this additional disturbance

Table 2.2 The mean values and range of energy expended by aircrew flying a variety of helicopters in different situations

Source	Type of Aircraft	Number of Subjects	Mean and range of energy expended ($kcal/m^2hr$) during: Rest	Routine flight (alt 500 ft)	Ascent	Hover close to ground	Emergency situation
Littell & Joy (1969)	OH-6A (light-weight)	12	53 (48-58)	49 (47-51)	64 (60-68)	67 (63-71)	-
	UH-1D (medium weight utility)	12	50 (46-54)	49 (47-51)	53 (49-57)	55 (50-60)	-
	CH 47A (heavy)	12	48 (42-54)	52 (50-54)	62 (58-66)	62 (60-64)	-
Billings et al (1970)	UH-12E) UH-12EL) (light utility)	4	48 (44-51)	73 (64-80)	85 (76-93)	97 (85-110)	-
Kaufman et al (1970)	J-CH3 (heavy duty)	12	53 (50-56)	52 (49-55)	-	-	83 (49-108)

is discussed in a later chapter of this thesis.

The review has also shown that while helicopter aircrew expend about the same energy as pilots of fixed wing aircraft when flight is routine and at an altitude well clear of ground obstacles, flight close to the ground (.e.g. hovering, ascent and descent) requires high physical activity on the part of the pilot and his metabolic energy expenditure is correspondingly high. Since hovering flight close to the ground may under certain conditions augment the structure borne vibration which is constantly present in aircraft of this type, the energy expended by the pilot may be very high indeed. The practical significance of this disturbance to helicopter aircrew is discussed in a later chapter of this thesis.

CHAPTER 3

Experimental Methods

3.1 The vibration generator and associated equipment

3.2 The experimental breathing system

3.3 Measurement of pulmonary ventilation

3.4 Measurement of end-tidal carbon dioxide concentration

3.5 Techniques in measurement of gaseous exchange

3.6 Measurement of cardiac frequency

CHAPTER 3

Experimental Methods

The experimental work described in this thesis was carried out primarily to investigate some of the effects of low frequency structure-borne, whole-body vibration on the human respiratory system. In particular two areas of investigation were undertaken.- one relating to the effects of whole-body vibration on pulmonary ventilation and the other relating to the effects on metabolic oxygen consumption. In the course of these experimental studies a number of techniques were employed which were common to both areas of study. In this chapter, the main experimental techniques used in the investigations are described in detail. Other experimental methods which were used to investigate specific problems related to the main study are described in the appropriate chapters of this thesis.

3.1 The vibration generator and associated equipment

(a) The vibrator

The vibration generator used in this investigation applied sinusoidal vibration to the buttocks of a seated subject by means of a hard platform which was oscillated in the vertical plane at frequencies between 2 Hz and 10 Hz. The essential working parts of this vibration rig are shown in diagram in figure 3.1. The vibrator consisted of a 5 hp electric motor which drove a crank

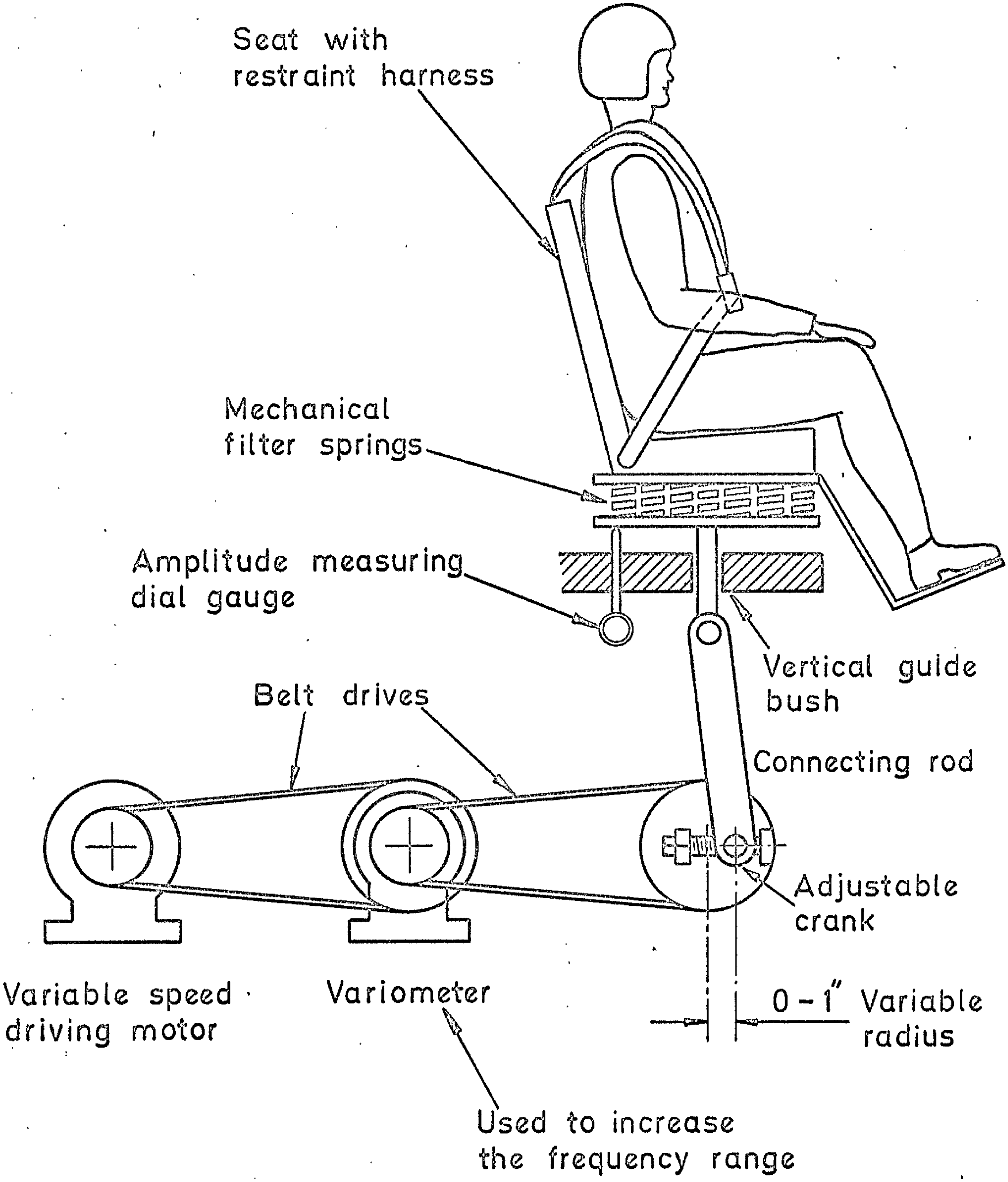


Figure 3.1 Diagram showing the essential working parts of the vibration generator.

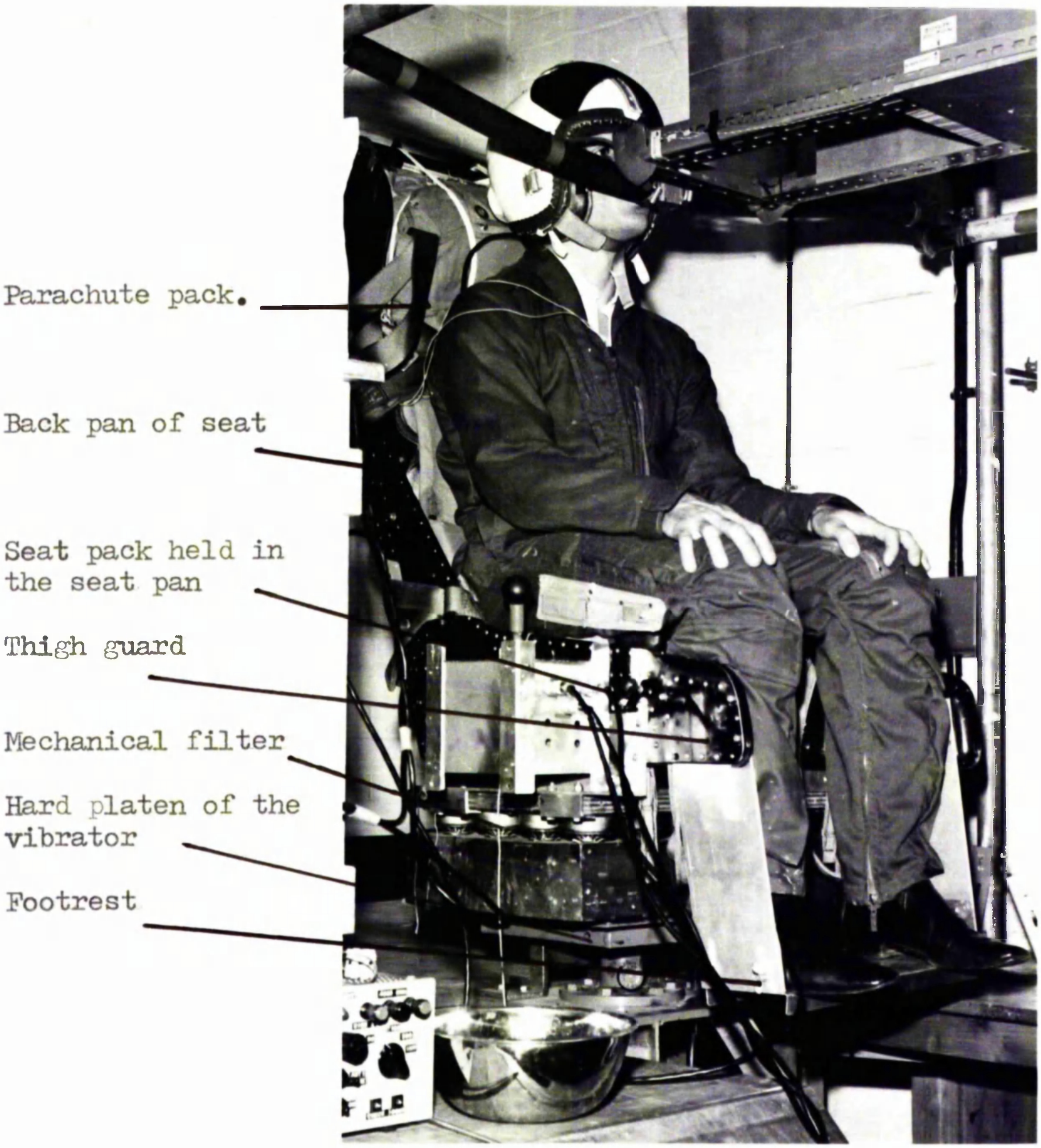
and piston rod connected to a hard steel platform upon which was mounted the seat used by the experimental subject. The frequency of vibration applied to the seat of the subject was varied between 2 Hz and 10 Hz by controlling the speed of the electric motor through a variable resistance. Fine adjustment of the frequency of vibration was achieved by means of a 'variator' (manufactured by Kopp Ltd) which was interposed between the drive shaft of the electric motor and the crank and piston rod to the vibration platform. The displacement double amplitude of the hard platform could be adjusted between 0 and 5 cm by varying the eccentricity of the rod connecting the platform to the drive of the electric motor. The double amplitude was measured after each adjustment had been made by means of a dial gauge which read to 0.001 inch.

In order to provide a comparable sitting posture to that normally adopted in flight, an aircraft ejection-type seat was mounted onto the hard platform of the vibrator. A low-pass mechanical filter, consisting of a series of 'anti-shock' mountings, was interposed between the base of the ejection seat and the hard platform of the vibrator. In this way the seat plus the mounting used by the experimental subject had a natural frequency of about 35 Hz. The vibration seat used in the experiments was constructed from a Martin Baker Type 4 ejection seat which had been salvaged from an aircraft accident but which had remained structurally intact. This type of ejection seat is commonly employed in military aircraft to allow the occupant to escape from the aeroplane in an emergency. It is a rigidly constructed seat which is forcibly ejected from the aircraft by a ballistic explosive charge and consists of a metal bucket-type seat (seat pan), a back support (back pan), headrest and sides which give lateral support to the legs (thigh guards). The seat pan normally contains a fibreglass 'seat-pack' which provides a sitting surface for the occupant of the aircraft and in which is contained a number of items required for purposes of survival at sea or on land after the occupant has escaped from the aircraft. The back pan of the seat contains a packed parachute which under normal circumstances of flight gives support to the back of the seated occupant.

In order to lighten the weight loading on the vibration generator, a number of structures was removed from the seat before it was mounted on the vibration platform. In the main, these superfluous structures were associated with ballistic ejection of the seat from the aircraft and their removal in no way interfered with the sitting posture adopted by the subject. The modified seat was next mounted on to the vibration generator by means of four steel clamps which secured the base of seat to the platform of the vibrator. A footrest was constructed from sheet steel and attached by bolts to the forward thigh guards of the ejection seat. In this way, the experimental subject seated in the ejection seat on the vibrator could position his feet and legs in a position similar to that adopted in an aircraft during flight. The footrest was provided with an adjustable rake which could be raised and lowered to suit variations of leg length in the experimental subjects. The items contained in the fibreglass seat pack were removed (e.g. inflatable liferaft, survival rations, etc), the shell of the container was strengthened using blocks of wood and it was then replaced in position in the bucket of the metal seat pan of the modified ejection seat. This fibreglass container provided the sitting surface for the occupant of the vibration seat. The packed parachute was retained in the back pan of the ejection seat and this served to provide back support for the seated subject. The photographs in figures 3.2 and 3.3 show the essential features of the modified ejection seat mounted on the vibration generator as well as the sitting posture adopted by the subject during the experimental procedures.

(b) Harness restraint system

In a number of experiments, the respiratory effects of whole-body vibration were studied with the experimental subject sitting fully restrained by a harness system incorporated in the seat. The results obtained in this way were compared with those obtained when the subject was completely unrestrained in the seat. For the purposes of this experiment a combined parachute and restraint harness system was incorporated in the modified ejection seat mounted on the vibrator. The system used in this investigation



<u>Figure 3. 2</u> Features of the modified ejection seat mounted on the vibrator

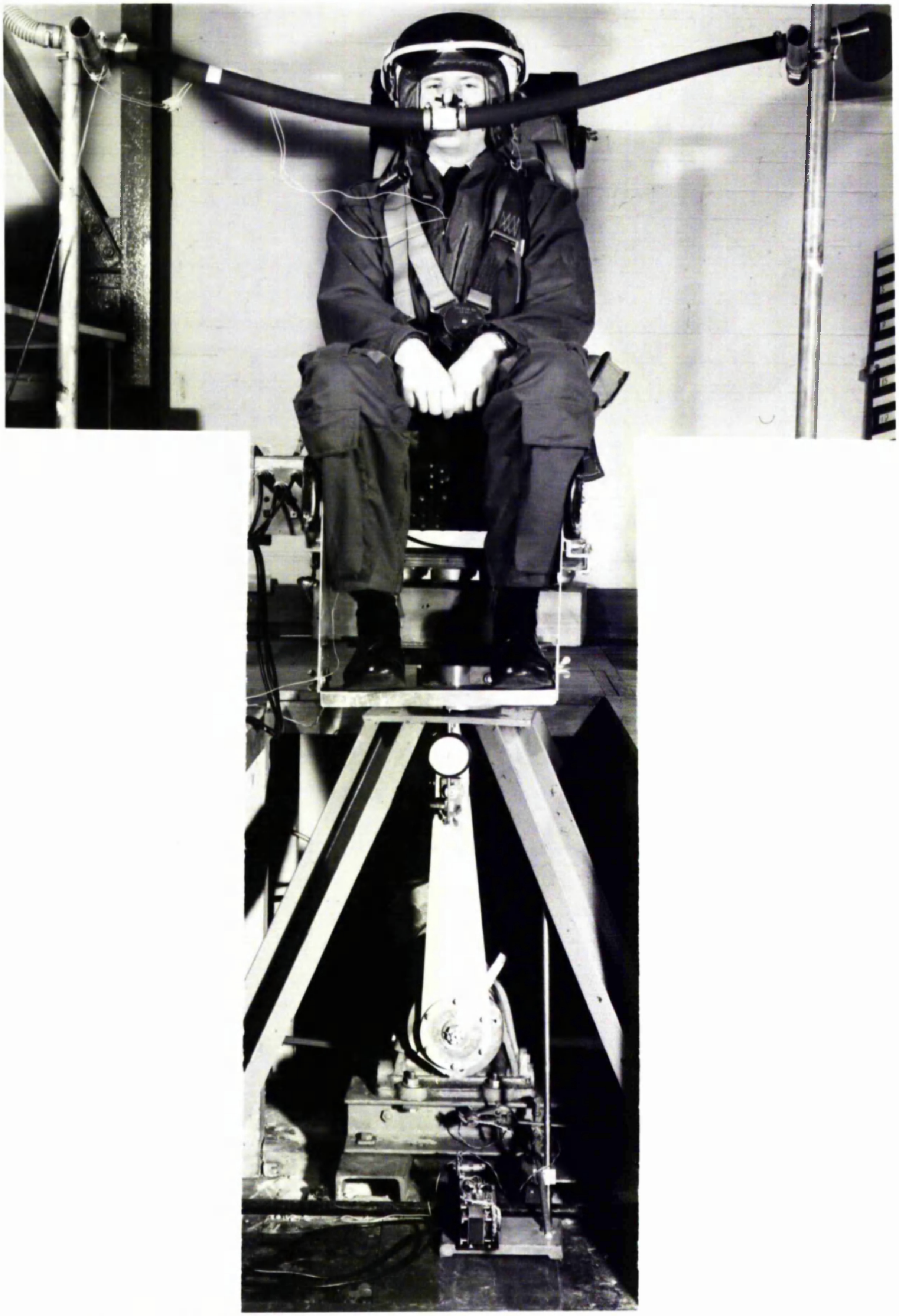


Figure 3. 3 Front view of the vibrator rig used in the experiments.

was typical of the type of harness restraint system used in current high performance aircraft and its efficacy in providing sound restraint of the subject in an aircraft seat against forces of acceleration and deceleration in various axes is well known and thoroughly tested (Reader - personal communication).

The main features of the harness system used in this study are shown in diagram form in figure 3.4. It consisted of two nylon webbing shoulder straps, two lap straps and a single 'tie-down' strap. This latter 'tie-down' strap (see figure 3.4) is a feature of modern harness restraint systems and serves to resist any upward pull of the shoulder straps during the application of negative acceleration and thereby prevents the subject from rising up off the seat and also prevents the lap straps from being displaced into the abdomen of the subject. Each harness restraint strap was provided with a tensioning buckle which allowed adjustment of the system to provide sound restraint in the seat. Each strap terminated in a metal lug which was inserted into the appropriate part of a single point attachment and release fitting. The harness system was adjusted in each case so that this fitting rested comfortably on the surface of the abdomen of the seated subject (see figure 3.4).

(c) Measurement of vertical acceleration of the vibration

In one series of experiments the total displacement amplitude of the vibration was held constant at 0.625 cm (0.25 in) over a

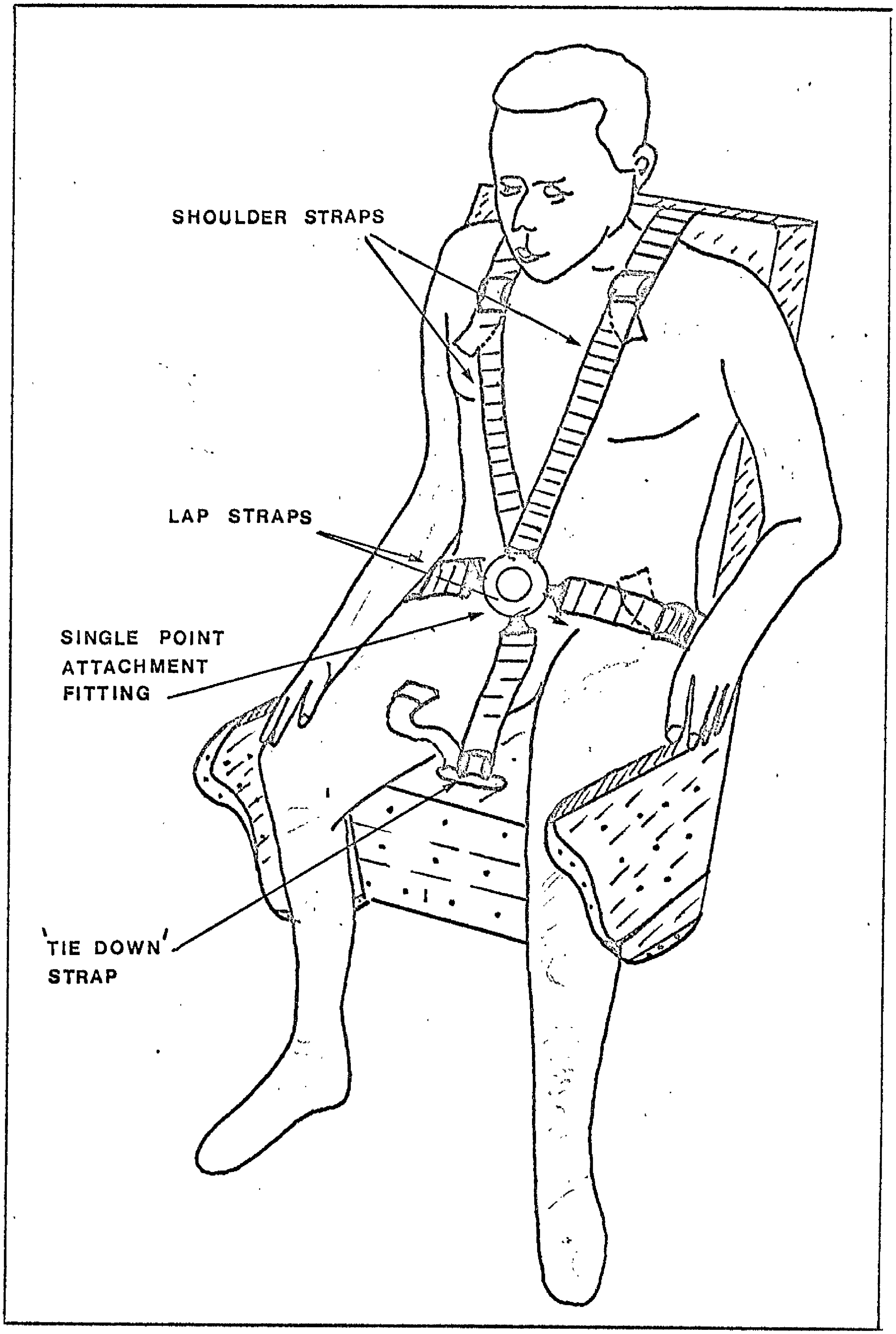


Figure 3. 4 Features of the harness restraint system.

frequency range 2 to 10 Hz which was explored in frequency steps of 2 Hz. In the other experimental series the displacement amplitude of vibration was adjusted between each vibration exposure in such a way as to maintain an acceleration of $\pm$ 0.4 G at the seat over the same frequency range. In each case the vertical acceleration of the seat during each experimental run was first calculated and then measured using a variable resistance accelerometer in conjunction with a carrier amplifier and recorder.

The calculated value of vertical acceleration was obtained using the following equation:-

$$\text{Vertical acceleration (G)} = \frac{4\pi^2 f^2 A}{386}$$

where A = half-wave amplitude (inch)

f = frequency of vibration (Hz)

and 386 is the International Standard Acceleration (inch-pound-second scale)

In each experimental session the vertical acceleration of the vibrating seat was recorded and displayed continuously throughout each period of vibration. For this purpose, a Statham variable resistance accelerometer (range $\pm$ 10 G) was mounted on the undersurface of the seat pack in the vibrating seat. In this way the acceleration data was recorded as close as possible to the buttocks of the seated subject. The output signal from the accelerometer was first amplified using an appropriate amplifier and then displayed on one channel of a Devices pen recorder. Calibration of this accelerometer was carried out before and after each experimental session by recording the output signal from the transducer first with it in the horizontal plane, then in the upright vertical plane and finally in the inverted plane. In this manner, calibration recordings of zero acceleration, + 1 G and - 1 G accelerations were obtained.

(d) Harmonic analysis of the applied sinusoidal vibration

The purity of the sinusoidal waveform as measured at the buttocks of the subject seated in the vibrating seat was analysed using a Digital Transfer Function Analyser, Type JM 1600 in conjunction with a Mechanical Reference Synchroniser, Type JX 1606 (both manufactured by Solartron Electronic Group Ltd). With this instrument, the sinusoidally varying input signal measured at the vibration seat was compared with a generated reference signal with respect to relative amplitude (displayed as root mean squared voltage) and phase angle. By selecting the appropriate band-pass filter, the amplitude and phase angle difference between the test and reference sinusoidal signals were measured for the fundamental frequency and for harmonic frequencies up to and including the 10th harmonic. In this way a spectrum analysis of the test waveform was carried out and this was expressed for each harmonic frequency component as a percentage value of the fundamental frequency.

The reference signal used in this analysis was obtained by attaching a thin strip of metal to the shaft of the motor drive to the eccentric of the vibration generator. With each revolution of the drive shaft, the rotating metal strip interrupted a light beam which was focussed onto a photoelectric cell. The intermittent signal thus obtained was first suitably amplified and then fed at an appropriate level of voltage into the Mechanical Reference Synchroniser. The signal to be measured was obtained by means of the Statham variable resistance accelerometer mounted in the seat pack of the vibrator seat, the output of which was suitably amplified and also fed into the Mechanical Reference Synchroniser.

Analysis was carried out of the vibration waveform at frequencies of 2, 4, 6, 8 and 10 Hz and with a total displacement amplitude of 0.625 cm. During each test vibration, a subject was seated fully restrained in the vibration seat. Table 3.1 summarises the results of this analysis, for each frequency of applied vibration. In each case, the harmonic content (up to the 10th harmonic) is expressed as a percentage of the fundamental frequency. It may be seen by reference to Table 3.1 that throughout the range of frequencies used in the investigation the distortion of the vibration waveform (measured at the buttocks) from its fundamental frequency was relatively small and for the purposes of this study could be considered acceptable.

Table 3.1 Harmonic analysis of the vibration waveform as measured at the vibrator seat

Harmonic	Harmonic content of waveform expressed as a percentage of the fundamental at vibration frequencies of (Hz):-				
	2	4	6	8	10
2nd	0.53	6.60	2.91	2.41	0.99
3rd	0.46	3.31	0.72	4.43	1.02
4th	0.69	0.36	0.72	0.24	0.28
5th	0.92	0.20	0.72	0.05	0.18
6th	1.07	0.83	0.36	0.41	0.26
7th	1.15	0.16	0.72	0.13	0.07
8th	1.46	0.88	0.36	0.46	0.28
9th	1.84	0.46	0.72	0.38	0.26
10th	2.07	1.03	0.72	0.36	0.52

3.2 The experimental breathing system

An experimental breathing system was designed and constructed in order to study the effect of vibration upon pulmonary ventilation and gaseous exchange. The subject breathed through an open circuit breathing system by means of a mouthpiece, whilst his nostrils were occluded using a nose clip. The mouthpiece was connected to a valve box which was fitted with two lightly spring-loaded mica disc valves. One mica disc non-return valve allowed one-way passage of inspired room air to the subject's respiratory tract, while the other non-return valve allowed expired gas to pass through widebore connecting tubing to respiratory recording and gas collection apparatus. In a similar vibration experiment, Ernsting (1961) found suitable non-return valves only after considerable preliminary experimentation. He found that conventional rubber flap valves failed to act as non-return valves under certain conditions of vibration. In the present investigation, therefore, only mica-disc valves were used throughout the experiments. The efficiency of these mica-disc non-return valves was assessed at intervals through the investigations, by carrying out simultaneous recordings of the flow pattern in both the inspiratory and expiratory hoses during all the conditions of vibration used in the study. In each case the results of these checks indicated that the valves were functioning satisfactorily even under the worst conditions of vibration.

The valve box and its mouthpiece were supported only by horizontally placed, thick-walled, connecting hoses. These hoses were made of nylon reinforced rubber with an internal diameter of 3.0 cm and were secured at each end to rigid metal pylons mounted on the platform adjacent to the vibrating seat at a distance of 1 metre on either side of the valve box (figure 3.3). Thick-walled, rubber hoses were used in order to eliminate any 'pumping' action due to movements transmitted to the hoses from the vibrating subject. The absence of any 'pumping' action was confirmed at frequent intervals throughout the study. For this check, the mouthpiece of the valve box was blanked off and the subject sat in the vibrating seat holding the blanked-off mouthpiece in his mouth and breathing through his nose. Vibrations were then applied to the seated subject at all frequencies and acceleration-amplitudes used in the experiments. Forward movement of gas along the conducting hoses due to any 'pumping' action was detected and measured by means of a heated Fleisch flowmeter inserted into the expiratory hose. The flow signal thus obtained was amplified using a suitable amplifier and then converted by electronic integration into a volume signal which was displayed on one channel of a Devices pen recorder. Any forward movement of gas was also measured by means of a 10 litre Parkinson Cowan dry gas meter which was inserted into the expiratory conducting hose. The results of these tests showed that under all the conditions of vibration used in the present experiments, movement of gas in the conducting hoses, as a result of transmitted 'pumping' action, was negligible.

Resistance to breathing through the circuit

The resistance to breathing through the experimental circuit was measured, first for that portion of the system between the inspiratory port and the mouthpiece (inspiratory resistance), and then for the portion between the mouthpiece and the expiratory port of the circuit (expiratory resistance). Included in the resistance imposed by the expiratory side of the breathing circuit was the ventilation volume measuring equipment together with a length of wide bore conducting hose. Air was passed through the inspiratory and expiratory portions of the breathing circuit at known flows (up to 100 litres (ATPD) and in steps of 20 litres (ATPD) per minute). The pressure drop associated with each flow of gas through each portion of the circuit was measured and the results of these measurements are presented graphically in figure 3.5.

3.3 Measurement of Pulmonary Ventilation

In a number of the experimental studies, measurements were made of minute volume ventilation, tidal volume and respiratory frequency with the subject at rest, during the period of chosen vibration and during the subsequent recovery period. For this, expired gas from the subject was conducted to a modified dry gas meter using flexible wide-bore hose. The gas meter used in the study (10 litre 'Spirometer' model manufactured by Parkinson & Cowan) was modified in such a way that a continuous record of expired gas volume could be displayed on a pen recorder. The modification to the gas meter consisted of the addition of a continuous rotation type precision potentiometer (type D8468/1 manufactured by Penny & Giles Ltd) the spindle of which was

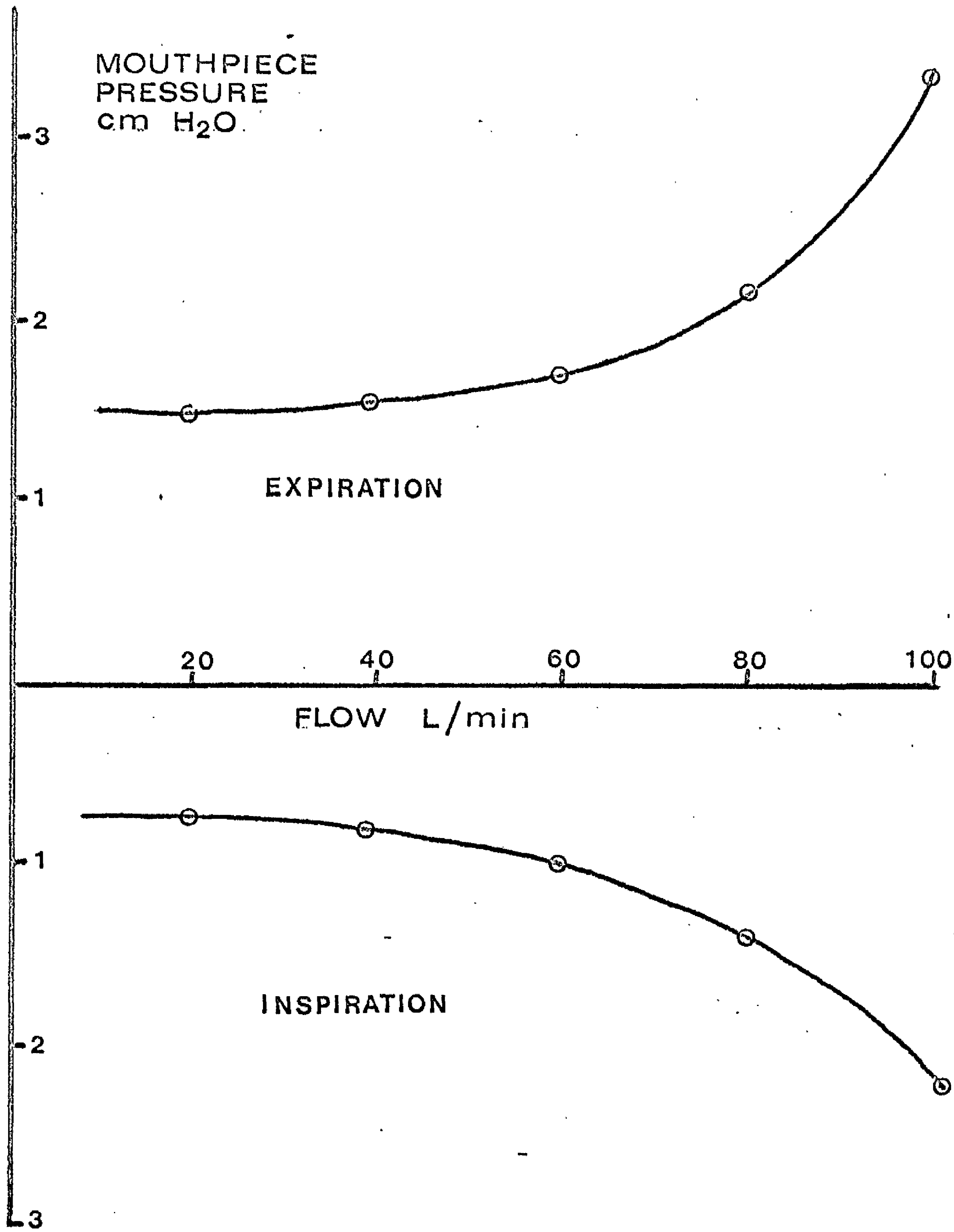


Figure 3. 5 Resistance of the breathing circuit to inspiration and expiration.

attached indirectly to the rotary shaft driving the needle pointer on the volume indicator dial of the meter. One complete revolution of the needle pointer on the gas meter (corresponding to the passage of 10 litres of expired gas) rotated a contact wiper arm through an angle of 360^o on the electrical coil winding of the potentiometer. This caused a variation in a standing voltage applied to the potentiometer coil winding which was proportional to the volume of gas which had passed through the gas meter. The voltage output signal from the potentiometer was then fed directly into one channel of a Devices pen recorder. A break in the winding of the potentiometer coil between the angles 357^o and 360^o allowed the recording pen to return to the base-line, zero position of the trace record after a total of 10 litres of gas had passed through the meter.

The accuracy of the modified gas meter in measuring gas volume was assessed by measuring values of expired gas volume obtained with the subject at rest and during two levels of physical activity and comparing the results obtained from the modified gas meter with those obtained by collection of the same gas volume and subsequent measurement using a water sealed (wet) gas meter.

For this part of the assessment, the subject sat on a bicycle ergometer and breathed room air using a mouthpiece attached to a light-weight valve box. The nasal passages were occluded by means of a suitable nose clip. Expired gas from the subject was conducted by wide bore smooth-walled flexible tubing from the expiratory port of the valve box to the inlet port of the recording gas meter. After passing through the experimental gas meter, the expired gas was next collected in a plastic Douglas bag (volume 100L) and the collected gas volume was later measured using a water sealed gas meter. The volume of gas which passed through the recording gas meter was measured by recording the output signal from the potentiometer mounted on the rotary shaft of the gas meter needle pointer. This signal was fed directly on to one channel of a Devices pen recorder. In this way a continuous record of expired gas volume was displayed on the pen recorder. The temperature of the gas entering the gas meter and the temperature of the room air was measured using mercury-in-glass thermometers. Measurement and collection of expired gas volume was carried out first with the subject seated at rest and then during light and moderate exercise on the bicycle ergometer. During each of these activities, gas volume measurements and collections were carried out over periods of three minutes. During the periods of exercise the subject pedalled the bicycle ergometer at a rate of 70 pedal revolutions per minute and brake band tensions of 1.25 Kg and 2.25 Kg for light and moderate exercise respectively. The external work loads thus applied were 290 kg m/min and 540 kg m/min respectively for the two levels of physical activity. The volumes of expired gas obtained from the subject during each physical activity were measured from the record obtained with the experimental gas volume recording system and these were compared with the volume collected in the Douglas bag and measured using the water sealed gas meter. All volumes were converted to STPD (Standard temperature and pressure, dry) and BTPS (Body temperature and pressure saturated with water vapour). The results of this comparison of the two methods of volume measurement are shown graphically in figure 3.6 which plots the ratio of the actual respired volume (as measured on the wet gas meter) to that indicated by the experimental dry gas recording system. It may be seen from this figure that for a total of 30 estimations (range of pulmonary ventilation 7 - 46 Litre/min) the modified dry gas meter tended to underread in the lower range of values of respired volume. For 30 estimations, the factor (k) needed to correct the volume indicated by the recording dry gas meter to the actual respired volume (BTPS) was 1.02 ± 0.025.

3.4 Measurement of end-tidal carbon dioxide concentration

During a number of experiments in the present investigation the instantaneous concentration of carbon dioxide in the gas leaving the respiratory tract was recorded with the subject at rest, during the period of whole-body vibration and during subsequent recovery. For this purpose an infra-red Carbon Dioxide analyser (Beckman Model, LB-1, Medical Gas Analyser) was used.

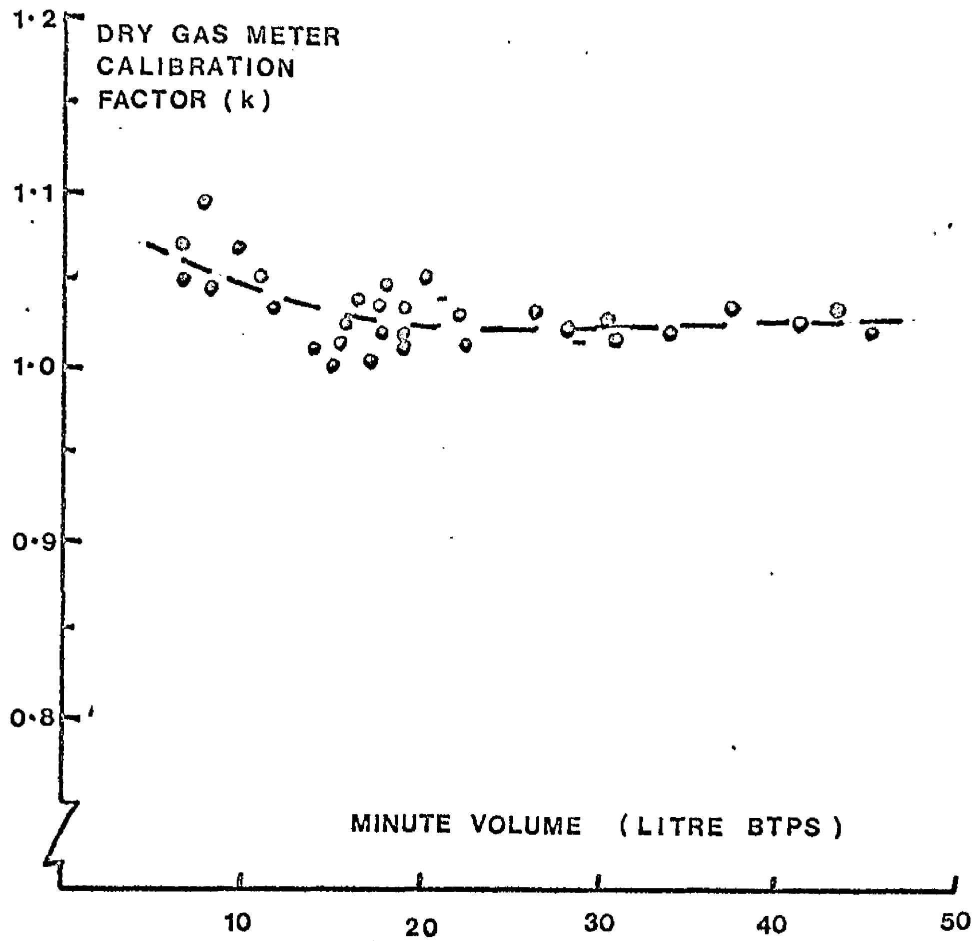


Figure 3. 6 Calibration factors for the dry-gas meter plotted against minute volume

This carbon dioxide analyser operates on the principle that carbon dioxide absorbs infra-red radiation. The analyser contains two parallel sources of infra-red radiation, one of which passes through a reference cell and the other through a sampling cell. The radiation falls on a detector cell which contains carbon dioxide under reduced pressure and which is divided by a flexible diaphragm which forms one plate of a variable capacitance. When infra-red radiation is absorbed by carbon dioxide in the sampling cell, a differential pressure is created in the detector cell and this alters the capacitance of an oscillation circuit. The output signal from this oscillator is rectified to give a direct voltage which is then amplified and fed onto one channel of a suitable pen recorder.

During the experiments in the present study, a continuous sample was taken of the gas passing through the mouthpiece used by the experimental subject. This was drawn through a fine bore polyethylene tube by means of a vacuum pump and delivered into the measuring head of the carbon dioxide analyser (which was mounted close to the subject). The output of the amplifier of the carbon dioxide analyser was displayed on one channel of an Esterline-Angus pen recorder. The analyser was calibrated immediately before and after each experimental procedure using calibration gases obtained from cylinders containing four different mixtures of carbon dioxide in air, the concentrations of which spanned the scale of values expected during the experimental runs. The calibration gas mixtures had been previously analysed using a Lloyd-Haldane apparatus and repeated samples had to agree to within 0.02%. The end tidal carbon dioxide concentration was determined from the maximum amplitude of the deflection recorded on the pen recorder during each expiration, and from the curve constructed from the calibration data. A typical calibration curve for the infra-red carbon dioxide analyser is shown in figure 3.7.

The accuracy of the infra-red carbon dioxide analyser was checked by comparing results obtained simultaneously using a respiratory mass spectrometer, MS4 (known to be able to measure carbon dioxide to within $\pm$ 2% of full scale deflection). A subject was made to hyperventilate after a period of rest and a comparison was made between the readings given by the Respiratory Mass Spectrometer and the carbon dioxide analyser. The results of this comparison are given in Table 3.2 from which it can be seen that the differences between the two analyses were random.

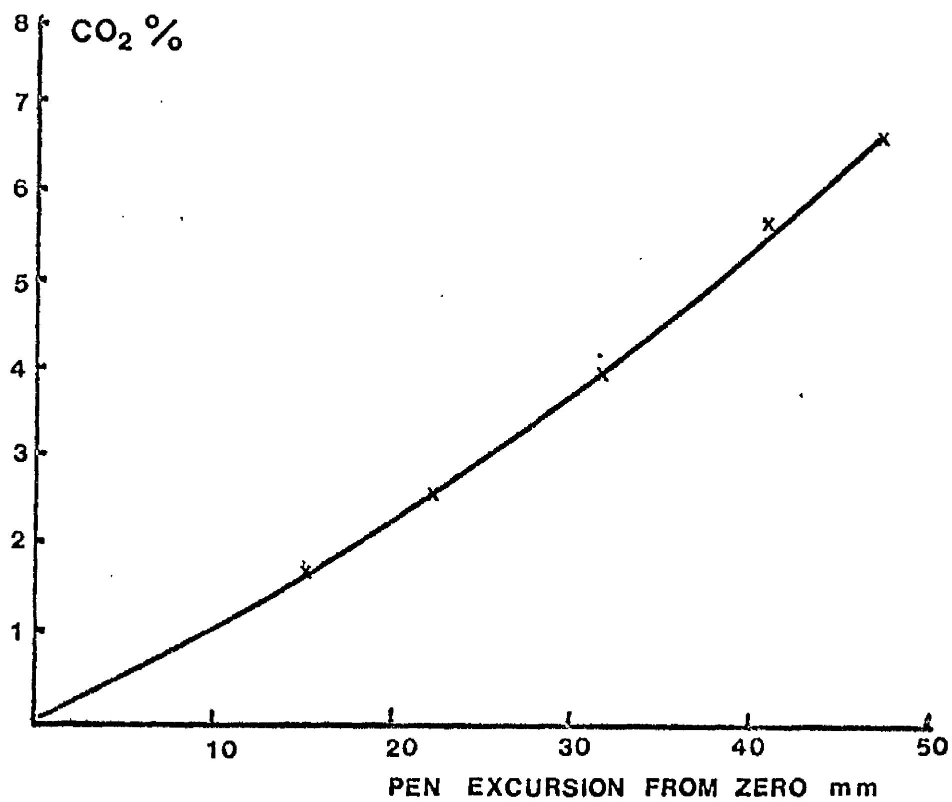


Figure 3. 7 Typical calibration curve for the infra-red carbon dioxide meter.

Table 3.2 Comparison of the end tidal carbon dioxide concentration measured with the infra-red analyser and the respiratory Mass Spectrometer

Carbon dioxide concentration (%) measured by :		
Infra-red analyser (1)	Mass Spectrometer (2)	Difference (1 - 2)
5.53	5.50	+ 0.03
5.62	5.60	+ 0.02
5.41	5.44	- 0.03
5.80	5.85	- 0.05
4.76	4.78	- 0.02
4.34	4.32	+ 0.02
3.22	3.26	- 0.04

A further test was carried out in order to measure the rise time of the carbon dioxide analyser and to assess its ability to cope with measurements should hyperventilation and an increase in respiratory rate occur during any of the experimental procedures. For this test, the sampling line from the measuring head of the analyser was inserted into one limb of a Douglas tap and air which contained carbon dioxide was fed into another limb of the tap. By opening the tap, the analyser could be switched rapidly from sampling room air to air containing carbon dioxide. With this technique it was found that the rise time of the analyser-recorder system for 90% response was less than 0.2 seconds. This was considered adequate for recording end-tidal carbon dioxide concentration at all respiratory frequencies expected in the experiments.

3.5 Techniques in measurement of gaseous exchange

In a number of experiments expired gas was collected from the subject during a period of rest, during the chosen vibration condition and during subsequent recovery from vibration exposure. In each case the collection of expired gas was made using a plastic Douglas bag (volume 100 L) and Douglas tap connected to the expiratory portion of the experimental breathing system. Analysis of the contents of the bag was carried out either immediately after collection or within 10 minutes following collection in order to minimise inaccuracies due to gaseous diffusion through the wall of the plastic bag. The contents were analysed for oxygen and carbon dioxide concentrations and from these data calculations were made of metabolic oxygen consumption, carbon dioxide output and respiratory exchange ratio.

The actual experimental procedure involved in the collection of expired gas at various times during the experimental procedure will be dealt with in the appropriate chapter of this thesis. In this section, however, a brief description of the technique used to obtain data necessary for the calculation of gaseous exchange in the experimental subject will be given.

(a) Measurement of expired gas volume

Expired gas volumes were measured using the recording gas meter which has been described fully in a previous paragraph. During the period when collection of expired gas for analysis was carried out, a record of gas volume passing through the recording gas meter was obtained on one channel of a Devices pen recorder. The temperature of the gas entering the inlet port of the gas meter was measured at intervals of half a minute over the three minute collection period and the mean temperature thus obtained was used in the conversion of the measured volume of gas to STPD. Ambient room temperature was also measured and the atmospheric pressure during the experimental run was obtained from a wall-mounted mercury barometer.

(b) Measurement of expired carbon dioxide concentration

After collection the contents of each Douglas bag were analysed for carbon dioxide concentration. The content of the collection bag was first thoroughly mixed by vigorous and frequent agitation and a quantity of gas (about 500 ml) was expelled under pressure through the sampling side-tube of the Douglas bag in order to purge out any residual gas therein. Part of the contents of the bag was then expelled through the side-arm sampling tube, through a column of silica-gel drying crystals and subsequently into the measuring head of the infra-red carbon dioxide analyser. A description of this measuring equipment and the performance characteristics have been given in a previous paragraph. The output from the carbon dioxide analyser was fed onto one channel of an Esterline Angus pen recorder. The concentration of carbon dioxide in the collected expired gas sample was obtained by noting the maximum deflection of the pen and by reference to the calibration curve for carbon dioxide previously constructed. This procedure was repeated on four occasions.

(c) Measurement of expired oxygen concentration

The remaining contents of the Douglas bag were analysed for expired oxygen concentration. For this purpose a Beckman model E2 oxygen analyser was used. This analyser operates on the principle that oxygen is strongly paramagnetic (attracted into a magnetic field) as distinct from most other gases which are diamagnetic (repelled out of a magnetic field). The heart of the measuring system is a hollow glass dumbell suspended on a taut quartz fibre in a magnetic field. When no oxygen is present, the magnetic force exactly balances the torque of the quartz fibre and the dumbell remains stationary. When a gas sample containing oxygen is drawn into the chamber surrounding the dumbell, the magnetic force is altered and the dumbell rotates -- the degree of rotation being proportional to the concentration of oyxgen. A small mirror attached to the dumbell throws a beam of light onto a translucent scale and measurement of oxygen concentration is made by adjusting a voltage (by means of a precision potentiometer) to return the light beam to a central 'null' position on the translucent scale. The reading of oxygen concentration is taken directly from the potentiometer dial which has 1000 divisions.

The oxygen analyser was calibrated at frequent intervals throughout each experimental run using gases from cylinders which contained oxygen in air in concentrations which spanned the scale of values expected during the experiments. The calibration gas mixtures had been previously analysed using a Lloyd Haldane analysis apparatus. To measure the oxygen concentration in the sample of expired gas obtained from the subject at each collection, the content of the Douglas bag was once again mixed thoroughly by agitation and a quantity of gas was expelled through the sampling side tube of the bag to purge out unwanted residual gas. The content of the bag was passed through silica-gel drying crystals and then into the oxygen analyser at a rate of 250 ml/min. Readings of oxygen concentration were taken on three separate occasions for each collection sample and these were required to agree to within an oxygen concentration of 0.02% of each other.

A diagram of the experimental breathing system, gas collection and measuring equipment used in the study is shown in figure 3.8.

(d) Calculation of metabolic oxygen consumption

From the data obtained by analysis of expired gas from the experimental subject (oxygen and carbon dioxide concentrations and

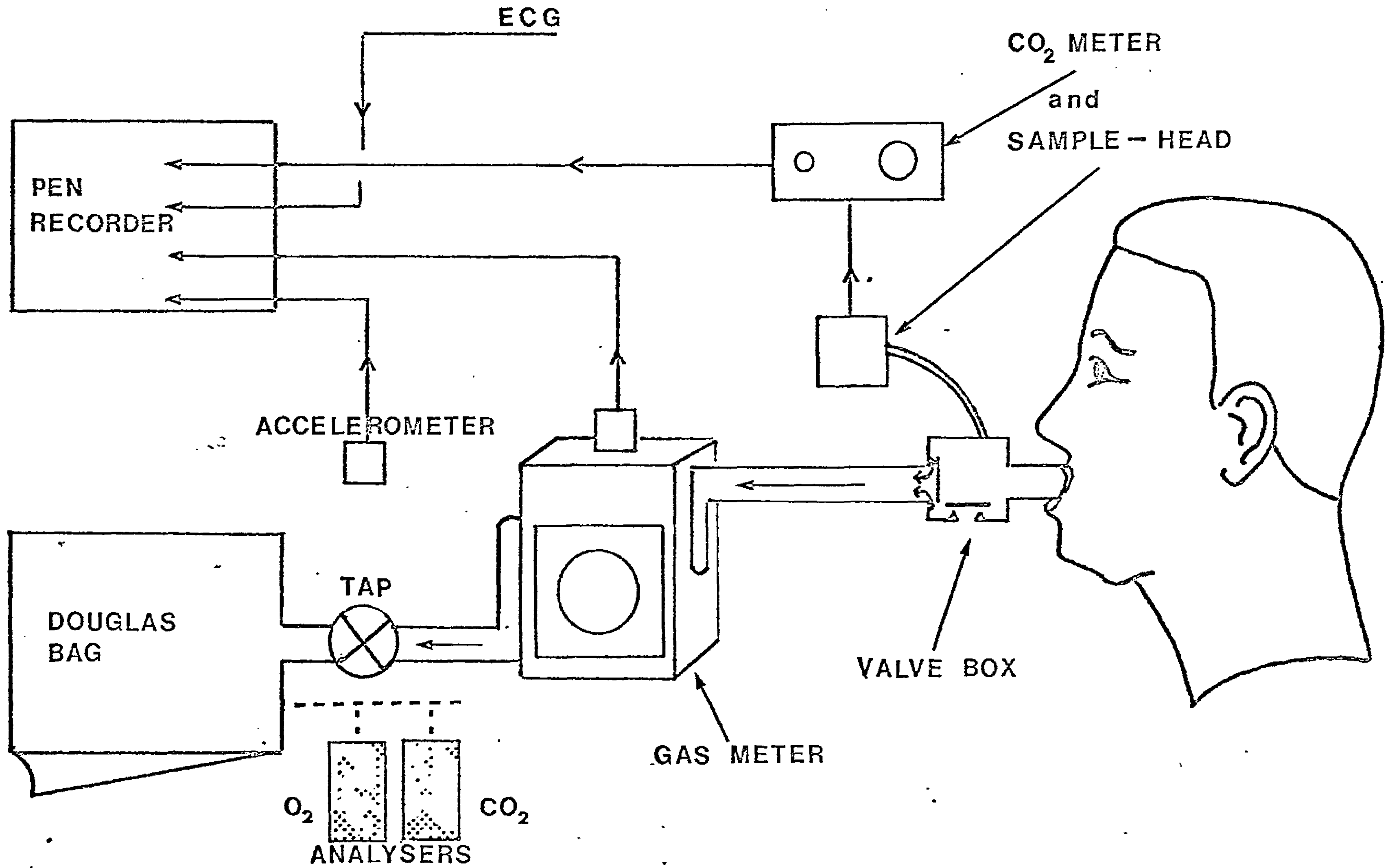


Figure 3. 8 Diagram of the experimental equipment used in the study.

by exclusion nitrogen concentration) metabolic oxygen consumption was calculated using the following equation:-

$$\dot{V}O_2 = (\dot{V}_I \times F_{I_{O_2}}) - (\dot{V}E \times F_{E_{O_2}})$$

where $\dot{V}O_2$ = oxygen uptake per minute (Litre, STPD)

$\dot{V}_I$ = inspired minute volume (Litre, STPD)

$\dot{V}E$ = expired minute volume (Litre, STPD)

$F_{I_{O_2}}$ = fractional concentration of inspired oxygen

$F_{E_{O_2}}$ = fractional concentration of expired oxygen

In order to obtain values for the inspired volume of gas (V_I) required in the calculation of metabolic oxygen consumption, a correction was applied to the measured expired gas volume using the following equation:-

$$\dot{V}_I = \frac{\dot{V}_E \times F_{E_{N_2}}}{F_{I_{N_2}}}$$

where $\dot{V}_I$ = the inspired minute volume ventilation (Litre, STPD)

$\dot{V}_E$ = the expired minute volume ventilation (Litre, STPD)

$F_{I_{N_2}}$ = the fractional concentration of nitrogen inspired (assumed for room air = 79%)

$F_{E_{N_2}}$ = the fractional concentration of nitrogen in expired gas (by exclusion)

(e) Calculation of carbon dioxide output

The volume of carbon dioxide produced by the experimental subject in one minute was calculated from the formula:-

$$\dot{V}_{E_{CO_2}} = \dot{V}_E \times F_{E_{CO_2}}$$

Where $\dot{V}_{E_{CO_2}}$ = volume of carbon dioxide excreted in expired air in one minute (Litre, STPD)

$\dot{V}_E$ = the expired minute volume ventilation (Litre, STPD)

$F_{E_{CO_2}}$ = fractional concentration of carbon dioxide in expired gas

(f) Calculation of the Respiratory Exchange Ratio

The Respiratory Exchange Ratio was calculated from the following equation:-

$$\text{Respiratory Exchange Ratio (R)} = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}}$$

where $\dot{V}_{CO_2}$ = volume of carbon dioxide excreted per minute (Litre, STPD)

$\dot{V}_{O_2}$ = metabolic oxygen consumption per minute (Litre, STPD)

For convenience, the equations used in the determination of $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$ and R were entered into a computer programme and the calculations were carried out using a digital computer.

3.6 Measurement of cardiac frequency

In some of the experimental vibration exposures, the cardiac frequency of the subject was measured using an electro-cardiograph (ECG). After a number of trials it was found that during vibration the most suitable ECG recording could be obtained by using self-adhesive ECG electrodes (manufactured by Devices Ltd), one electrode mounted on the skin overlying the manubrium sterni and the other on the skin surface overlying the cardiac apex. A third electrode affixed to the skin of the right ankle served as an earth lead. The ECG signal thus obtained was suitably amplified and displayed on one channel of a Devices pen recorder.

In one part of the investigation, the instantaneous cardiac frequency (time between successive 'R' waves of the ECG) was measured during the transition from rest to vibration exposure. The equipment for this purpose was constructed from a circuit designed by Whittle (personal communication) which measured and displayed R-R interval from the ECG on a second channel of a Devices pen recorder. With this apparatus, the output signal from the ECG amplifier was fed into a bandpass filter which filtered components of the ECG having frequencies on either side of a frequency band 5 - 15 Hz. The filtered ECG signal was next fed into the input of a level-sensitive monostable vibrator circuit which converted the signal to a square-wave output when the input signal exceeded a certain preset threshold value (the threshold value was adjusted so that the circuit was triggered only by 'R' waves of the ECG). The square-wave output was next differentiated electronically and the resultant signal was used to ground the input of an integration circuit and then to start a linear 'ramp' of voltage. In this way the arrival of an 'R' wave of the ECG started the voltage ramp and the succeeding 'R' wave stopped and reset the ramp. Thus the duration of ramp voltage output was proportional to R-R interval of the ECG wave. This voltage ramp output signal was fed directly on to a channel of a Devices pen recorder and the R-R interval of the ECG was displayed as a 'picket fence' record - the height of successive excursions of the recording pen from the base line indicating the duration of the R-R interval. The measuring equipment was calibrated using a electronic circuit which produced synthetic 'R' waves at various known time intervals.

CHAPTER 4

Experimental studies on the effects of constant amplitude vibration on the respiratory system

CHAPTER 4

Experimental studies on the effects of constant amplitude vibration on the respiratory system

4.1 Introduction

In the preceding chapters it was shown that there is very little information regarding the effects of structure-borne whole-body vibration on the human respiratory system. In particular, attention was drawn to two areas in this field which have considerable practical importance in aviation medicine and in which there is a paucity of knowledge. The first of these concerns the effects of low frequency vibration on pulmonary ventilation and gaseous exchange. The second area which has been relatively unexplored relates more specifically to the effects of low frequency whole-body vibration on metabolic oxygen consumption.

In previous investigations of the human responses to low frequency whole body vibration, research workers have exposed their experimental subjects to conditions of vibration in which the relationship between the displacement amplitude and frequency varied in two ways. Some investigators have used vibrations in which the amplitude was held constant and the intensity of the vibration increased with an increase in frequency. In other studies the amplitude of the vibration platform was adjusted in such a way as to maintain constant acceleration over the range of frequencies studidd. In order to study a wide range of frequencies and intensities, both types of vibration exposure have been used to investigate the respiratory effects of whole-body vibration. In the first series of experiments described in this chapter, the total displacement amplitude of vibration was held constant at 0.635 cm over a frequency range 2 - 10 Hz, and in a second series of experiments (described in a later chapter), the amplitude of the vibrating platform was adjusted to maintain a constant acceleration of $\pm$ 0.4 Gz at the seat of the subject.

In the review of the literature it was shown that a number of previous authors have reported an increase in pulmonary ventilation in the subject exposed to low frequency whole-body vibration. A few previous workers have also observed that at certain frequencies and intensities of vibration the relative increase in pulmonary ventilation is out of proportion to the relative increase in metabolic oxygen consumption and that in these circumstances there is a true hyperventilation with a measurable hypocapnia. Others, however, have adduced evidence of hyperventilation during exposure of the subject to whole body vibration only by inference, and there is comparatively little known about the magnitude of this phenomenon or the nature of the conditions of whole body vibration which can give rise to it. In addition, there have been a variety of different explanations advanced for the occurrence of hyperventilation in the subject exposed to whole body vibration. Many of these are unsatisfactory and so the true nature of the causative factors involved still remains obscure.

The experiments which have been carried out in this series were designed therefore in order to study the effects of whole body vibration at a constant displacement amplitude and various frequencies, upon the pulmonary ventilation in the human subject. They were also designed to establish whether conditions of whole body vibration of this type could induce hyperventilation and hypocapnia in the subject and also to elucidate, if possible, the mechanism or mechanisms responsible for these respiratory changes.

A second objective in the present experiments was to define the metabolic activity in the subject exposed to whole-body vibration at a constant displacement amplitude and at various frequencies. Previous work in this field has shown that under certain conditions of whole-body vibration there may be an increase in metabolic activity in the exposed subject. The magnitude of such an increase in metabolic activity during whole-body vibration has not yet been satisfactorily defined and the nature of the vibration stimulus which induces this change is still obscure. In addition very little is known about the mechanisms involved in the increased metabolic oxygen consumption observed in the subject during whole body vibration. The present experiments were designed, therefore, to establish the metabolic energy expended by the human subject exposed to whole body vibration at a constant displacement amplitude and various frequencies up to 10 Hz. In an attempt to define the causative factors in this phenomenon, a study was carried out of the behaviour of muscle masses in the subject during each condition of vibration using a technique of high speed cine photography. Finally, a study was made of the metabolic oxygen uptake in the subject exposed to vibration whilst sitting in the vibrator seat fully restrained by harness and the results were compared with those obtained with the subject sitting in the seat completely unrestrained and required to maintain his posture in the face of the vibration.

The results of both parts of this experimental study are given in this chapter of the thesis, together with a discussion of the findings in relation to the practice of aviation preventive medicine.

4.2 Methods

Nine experimental subjects in the age group 23 - 42 years took part in the investigation. Details of their heights, weights and body surface areas are given in Table 4.1.

The experiments were carried out using a mechanical vibrator on which was mounted a modified aircraft type ejection seat fitted with appropriate parachute and seat packs. Details of the vibrator rig and seat have been given in the Methods section of this thesis. Vibrations at frequencies of 2, 4, 6, 8 and 10 Hz were used in this study and the total displacement amplitude of the vibrating platform was held constant at 0.625 cm. In this way the acceleration-amplitude of the applied vibration ranged from $\pm$ 0.05 Gz at a frequency of 2 Hz to $\pm$ 1.43 Gz at a frequency of 10 Hz. The acceleration of the vibration was measured at the seat of the subject by means of a variable resistance accelerometer (range $\pm$ 10 G) mounted on the under surface of the seat pack of the vibrating seat. The output signal from this accelerometer was suitably amplified and displayed on one channel of a Devices pen recorder. In this way a continuous record of the vibration acceleration was obtained throughout the period of vibration exposure. Each subject experienced whole-body vibration at each of the frequencies used in the study whilst seated in the vibrator seat in either of two conditions of restraint. In one condition, the experiment was carried out with the subject sitting fully restrained by means of an aircraft type restraint harness incorporated in the vibrating seat. In the second condition, the experiment was performed with the subject unrestrained and free to adopt whatever posture he desired. The exposure to each frequency of vibration and the condition of restraint were applied in a random fashion and the subjects were unaware of the object of the experiment.

Each subject wore a lightweight Royal Air Force pattern flying coverall and a standard Mk 2 RAF integral protective helmet. The protective helmet was carefully fitted to each subject using a

Table 4.1 Height, weight and body surface area of the nine experimental subjects

Subject	Height (cm)	Weight (kg)	Body surface area (m^2) *
AM	176.5	72.5	1.88
GS	173.9	74.1	1.87
AC	175.4	69.4	1.75
WW	175.3	72.9	1.88
DC	172.7	71.8	1.84
CW	174.6	66.4	1.77
GP	171.5	67.2	1.79
ED	190.5	74.1	2.02
PF	193.0	80.5	2.18

* Body surface area computed from the nomogram of Dubois (1936)

standard aircrew fitting procedure. Electrocardiograph leads were applied to the chest and right ankle and the subject was instructed to sit in the ejection seat, mounted on the vibrator platform. The subject sat with his feet resting lightly on the footrest which was attached to the vibrating seat.

The subject breathed through the experimental breathing circuit (previously described in the Methods chapter) using a mouthpiece whilst his nostrils were occluded by a suitable nose clip. The mouthpiece was connected to a valve box which had a small dead space and was fitted with lightly spring-loaded mica disc valves. Expired gas was conducted from the expiratory port of the valve box by means of wide bore, low-resistance tubing to the recording gas meter and gas collection equipment. These have been described in detail in a previous section. At each experimental session a control measurement of ventilation volume and a collection of expired gas was made over a period of three minutes during a five minute rest period. During this period heart rate and end tidal carbon dioxide measurements were also made. The subject was then exposed to the chosen conditions of vibration for a total period of 10 minutes during which measurements of pulmonary ventilation, end tidal carbon dioxide concentration and cardiac frequency were made continuously. Collection of expired gas was made on two occasions during the vibrations exposure. The first collection was made between the second and fifth minutes of vibration and the other collection was made between the seventh and tenth minutes of vibration. For convenience, the data obtained from these samples will be described hereafter as those obtained after five and ten minutes of vibration. The vibration exposure was followed by a five-minute recovery period during which measurements of pulmonary ventilation and end tidal carbon dioxide concentration were continued and a final collection of expired gas was taken. Pulmonary ventilation and respiratory frequency were calculated from the record obtained from the recording gas meter for each minute of the control, vibration and recovery periods. Cardiac frequency for each minute of the same period was calculated from the ECG recording. The metabolic oxygen uptake, carbon dioxide output and respiratory exchange ratio were calculated from pulmonary ventilation and the expired gas analyses.

As an additional experiment to this series, a study was made of the response of various groups of muscles of the body during exposure of the subject to vibration at frequencies of 2 - 10 Hz. In this part of the study the conditions of vibration exposure and the measurement of physiological variables were identical to those of the main experiment. The subject sat in the vibration seat (either restrained by seat harness or unrestrained) and he wore only a pair of bathing trunks. A high speed cinematograph film was taken of vibration runs at 2, 4, 6, 8 and 10 Hz using a Milliken cine camera which operated at a film speed of 500 frames per second. The high speed cine film was taken first with the subject at rest and then for two periods (each of 3 minutes duration) during each vibration exposure. After it was developed, the film was run at slow speed through a cine editor and a frame by frame analysis was made of the movements exhibited by various groups of muscles during vibration exposure at each frequency.

4.3 Results

(a) Acceleration-amplitude of vibration

During each of 90 experimental vibration exposures the acceleration-amplitude of the vibration was measured at the seat using a variable resistance accelerometer. The mean values and range of values for acceleration-amplitude of vibration thus obtained during the experiments are given in Table 4.2.

Table 4.2 Mean values and range of values of acceleration-amplitude of vibration measured during each experimental vibration run at frequencies of 2, 4, 6, 8 and 10 Hz

	Acceleration-amplitude of vibration ($\pm$ Gz) at a vibration frequency of (Hz)				
	2	4	6	8	10
Mean value	0.05	0.21	0.50	0.89	1.43
Range of values	(0.04-0.06)	(0.19-0.23)	(0.48-0.51)	(0.87-0.92)	(1.41-1.45)

(b) Pulmonary ventilation

Mean values of pulmonary ventilation obtained for each minute of the experiment with the subject at rest, during exposure to vibration and during recovery from the vibration are shown in figures 4.1 and 4.2. In figure 4.1, the results are given for conditions in which the subject was restrained and unrestrained in the vibration seat during exposure to vibration at frequencies of 2, 4, and 6 Hz. The results obtained with subjects exposed to vibrations at frequencies of 8 and 10 Hz are shown in figure 4.2. It may be seen from figure 4.1 that with exposure to vibration at frequencies of 2 Hz and 4 Hz there was no marked alteration in values of pulmonary ventilation over those obtained during the period of rest prior to vibration exposure. With vibrations at a frequency of 6 Hz, however, there was an increase in the mean values of pulmonary ventilation obtained during the vibration period. This increase in pulmonary ventilation occurred within the first minute of exposure, was greatest at the beginning of the vibration period and gradually declined although the vibration was maintained. Directly vibration at a frequency of 6 Hz was stopped, the pulmonary ventilation fell below the control level. It may be seen by reference to figure 4.2 that with exposure to vibrations at a frequency of 8 Hz there was a marked increase in mean values of pulmonary ventilation obtained during the vibration period and that the greatest increase was obtained with exposure to vibration at a frequency of 10 Hz. At both these frequencies, the increase in pulmonary ventilation was rapid after the onset of the vibration, was greatest at the start of the vibration period and gradually declined towards the end of the period of exposure. In both conditions of vibration the pulmonary ventilation fell below resting values as soon as the vibration was terminated.

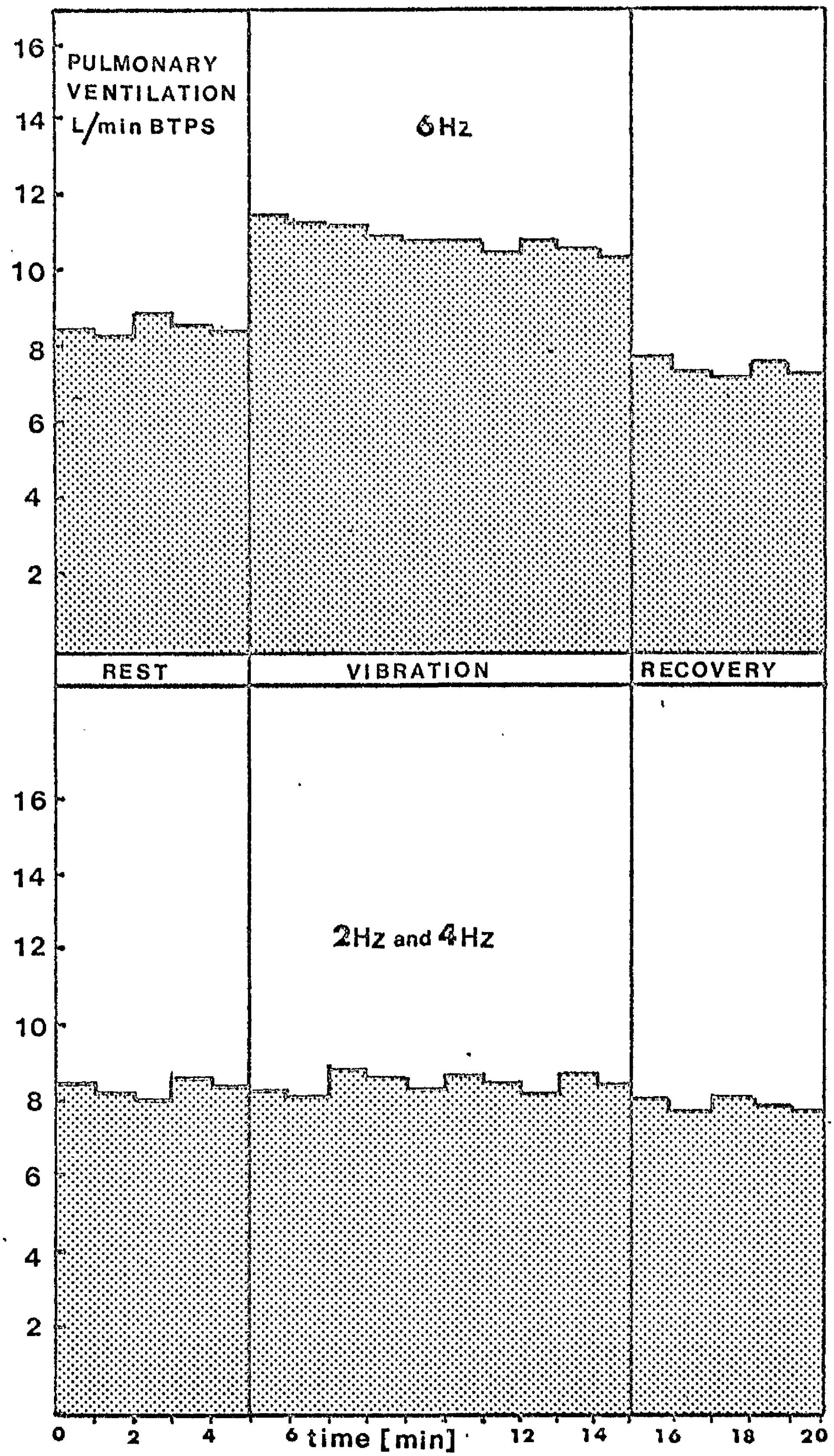


Figure 4. 1 Pulmonary ventilation during rest, vibration and recovery. Frequencies of 2,4 and 6Hz.

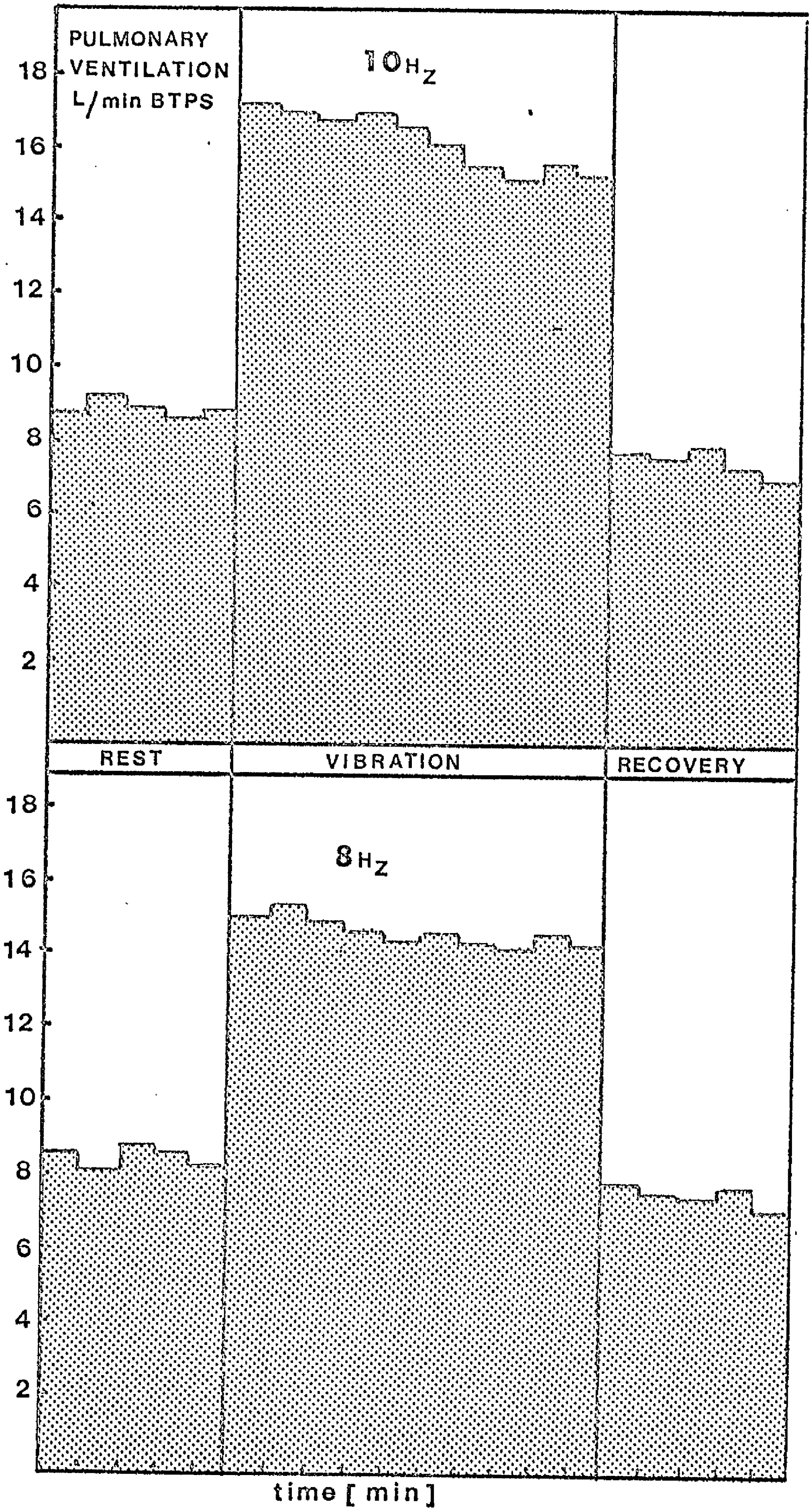


Figure 4. 2 Pulmonary ventilation during rest, vibration and recovery. Frequencies of 8Hz and 10Hz.

The mean values of pulmonary ventilation for all the subjects are shown in Table 4.3 for the period of rest, after 5 minutes and 10 minutes of exposure to vibration (frequencies range 2 - 10 Hz) and during subsequent recovery. The values obtained with the subject restrained in the vibration seat are shown together with those obtained when the subject was unrestrained in the seat.

Table 4.3 Mean values of pulmonary ventilation at rest, during vibration exposure and recovery from vibration. Nine subjects exposed to vibration (range of frequency 2 - 10 Hz) in restrained and unrestrained conditions

Frequency of vibration (Hz)	Pulmonary ventilation (L/min BTPS) during:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	8.74	8.51	7.87	8.27
4	8.21	8.68	8.20	7.62
6	8.74	11.64	10.80	7.37
8	8.55	13.51	14.53	7.62
10	8.60	16.36	15.40	7.95
		UNRESTRAINED		
2	8.59	8.64	8.12	7.94
4	8.40	9.14	8.25	7.13
6	8.64	11.41	9.81	7.85
8	9.49	14.60	13.93	7.94
10	8.53	14.56	13.15	7.21

The results obtained for pulmonary ventilation during the series of experiments were treated using an Analysis of Variance technique. The results of this analysis have shown that there was no significant difference between the values of minute volume ventilation obtained with the subject restrained and unrestrained in the vibrating seat. It has also shown that with vibration at frequencies of 2 and 4 Hz the pulmonary ventilation was not significantly increased beyond that obtained during the resting control period. At frequencies of 6, 8 and 10 Hz, however, the values of pulmonary ventilation obtained during the vibration period were significantly increased ($P = 0.001$) over those values obtained with the subject at rest. Furthermore, analysis has revealed that at these frequencies the increase in pulmonary ventilation after 5 minutes exposure to vibration was significantly greater than that obtained after 10 minutes exposure ($P = 0.01$). In these exposures in which the ventilation was greatly increased (at frequencies of 6, 8 and 10 Hz) during vibration, the values obtained in the recovery period were significantly reduced below the control resting level ($P = 0.001$). The mean values of pulmonary ventilation with subjects at rest, during exposure to vibration at frequencies of 2 - 10 Hz and during recovery are shown graphically in figure 4.3. In the data used to construct this figure, the values obtained with subjects restrained and unrestrained in the vibrating seat have been pooled.

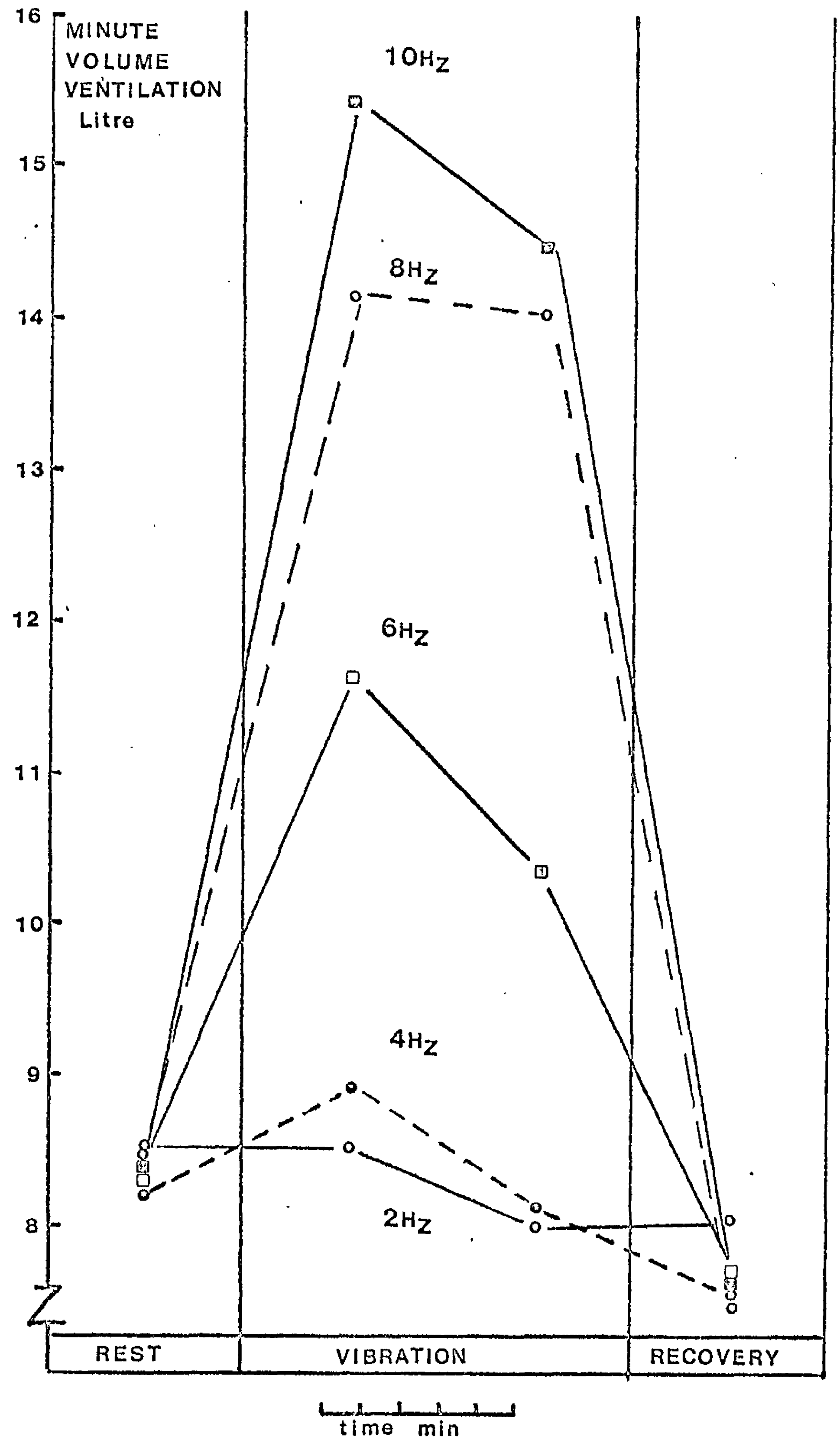


Figure 4. 3 Mean values for pulmonary ventilation during exposure to constant amplitude vibration.

(c) Respiratory frequency

Mean values of respiratory frequency obtained with the subject at rest, after 5 minutes and 10 minutes exposure to vibration (frequencies 2 - 10 Hz) and during recovery are shown in Table 4.4. In this table the results are given for the conditions in which the subject was restrained and unrestrained in the vibrating seat.

Table 4.4 Mean values of respiratory frequency with subject at rest, during vibration exposure (frequency range 2 - 10 Hz) and during recovery. Nine subjects, restrained and unrestrained in the vibrating seat

Frequency of vibration (Hz)	Frequency of respiration (Breaths/min) during:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	12.4	12.9	11.1	12.8
4	12.5	12.4	11.4	11.6
6	12.1	13.8	12.4	11.9
8	13.2	15.7	15.6	12.1
10	13.2	17.9	15.3	12.5
		UNRESTRAINED		
2	11.9	11.4	10.3	10.9
4	12.3	11.6	10.6	10.6
6	11.9	15.2	12.7	11.7
8	12.7	17.0	14.7	13.2
10	14.0	18.7	16.3	12.5

Analysis of the data has shown that significant changes in respiratory frequency occurred during the period of vibration at frequencies of 6, 8 and 10 Hz but not at frequencies of 2 and 4 Hz. Thus, it has been shown that with vibrations at frequencies of 2 and 4 Hz there was no change in respiratory frequency above those values obtained during the period of rest. With vibrations at frequencies of 6, 8 and 10 Hz there was a marked increase in respiratory frequency during the period of vibration. These values differed significantly from the values obtained during the period of rest ($P = 0.001$). Furthermore, it has been shown that the increase in respiratory rate at those frequencies of vibration was greatest after 5 minutes vibration exposure and declined towards resting values after 10 minutes of vibration exposure. There was no significant difference between values of respiratory rate obtained during the recovery period from those values obtained with the subject at rest. With all conditions of vibration exposure, there were no significant differences between the values of respiratory rate obtained with the subject restrained and unrestrained in the vibrating seat. The mean values for respiratory frequency with the subject at rest, during vibration exposure and during recovery from vibration are shown graphically in figure 4.4. In constructing this graph, the values of respiratory frequency in the two conditions of the experiment (subject restrained and unrestrained in the vibration seat) have been pooled.

(d) Tidal volume

Mean values of respiratory tidal volume obtained with the subject at rest, after 5 minutes and 10 minutes exposure to vibration at frequencies from 2 - 10 Hz, and during subsequent recovery from the vibration, are shown in Table 4.5. In this table the results obtained with the subject restrained in the vibrating seat are given together with those obtained with the subject unrestrained in the vibrating seat.

Analysis of the data has shown that the values for tidal volume obtained in all conditions of the experiment were not significantly different for the conditions in which the subject was restrained or unrestrained in the vibration seat. It has also shown that at frequencies of 2, 4 and 6 Hz there was no significant change in tidal volume during the vibration period from that obtained with the subject at rest. At frequencies of 8 and 10 Hz, however, there was a marked increase in values of tidal volume during the vibration period and these were significantly greater than those obtained during the period of rest ($P = 0.001$). Unlike the changes in respiratory frequency, analysis has shown that the increases in tidal volume during periods of vibration at frequencies of 6, 8 and 10 Hz were sustained throughout the period of vibration and no significant

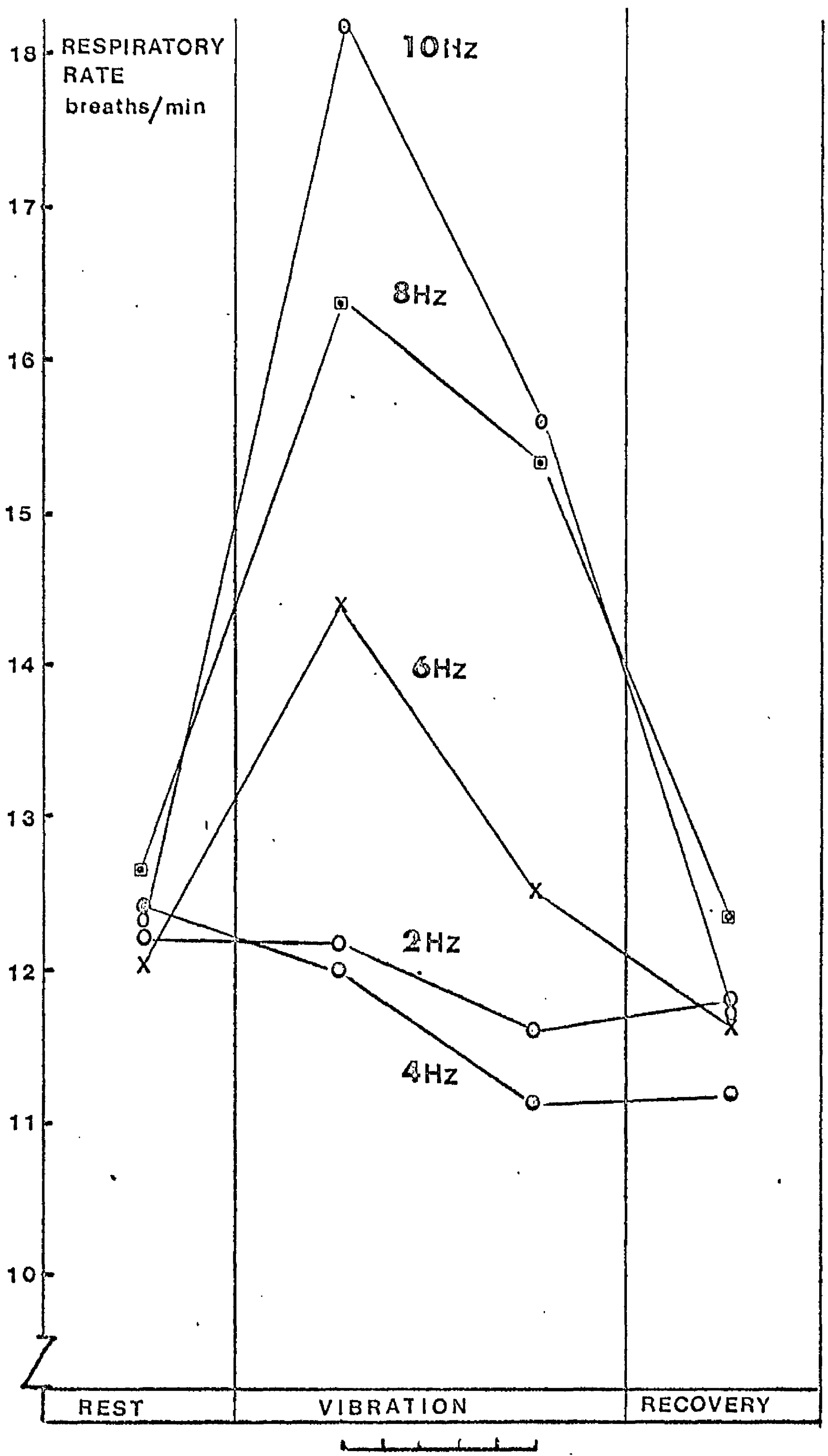


Figure 4. 4 Mean values for respiratory frequency during exposure to constant amplitude vibration.

Table 4.5 Mean values of tidal volume obtained with subjects at rest, during a period of vibration exposure and during recovery from vibration. Results for nine subjects restrained and unrestrained in the vibrating seat

Frequency of vibration (Hz)	Tidal volume (Litre, BTPS) during:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	0.71	0.68	0.71	0.69
4	0.69	0.76	0.74	0.68
6	0.75	0.77	0.80	0.68
8	0.74	0.91	0.99	0.65
10	0.65	0.99	0.97	0.64
		UNRESTRAINED		
2	0.78	0.81	0.83	0.76
4	0.73	0.75	0.78	0.71
6	0.74	0.74	0.80	0.67
8	0.71	0.93	0.98	0.67
10	0.73	0.94	0.98	0.70

differences could be detected between values obtained at 5 minutes and 10 minutes after the start of vibration. In the conditions of the experiment where tidal volume showed a marked increase over values obtained at rest, there was a significant fall in values of tidal volume ($P = 0.001$) below those obtained with the subject at rest. Mean values for tidal volume with subjects at rest, after 5 minutes and 10 minutes exposure to vibration at frequencies of 2 - 10 Hz and during subsequent recovery are shown graphically in figure 4.5. In constructing this graph, the values of tidal volume in the two experimental conditions (subject restrained and unrestrained in the seat) have been pooled.

(e) End tidal carbon dioxide tension

The results of the effects of whole-body vibration upon the end tidal carbon dioxide tension are presented in Table 4.6.

Table 4.6 The effect of whole-body vibration at frequencies of 2, 4, 6, 8 and 10 Hz upon end tidal carbon dioxide tension. (Pooled values for 9 subjects restrained and unrestrained in the vibrator seat.)

Frequency of vibration (Hz)	Mean values of end-tidal carbon dioxide tension (mm Hg) during :			
	Rest	After 5 min vibration	After 10 min vibration	Recovery 4 min
2	39.6	38.7	38.9	38.5
4	40.1	39.6	39.3	38.7
6	39.4	36.2	35.8	37.5
8	39.8	33.7	34.1	36.1
10	39.2	32.8	33.4	36.9

The mean control value for carbon dioxide tension obtained with the subject at rest is shown together with the mean values which existed after five minutes and ten minutes exposure to vibration at frequencies of 2, 4, 6, 8 and 10 Hz. The mean values of

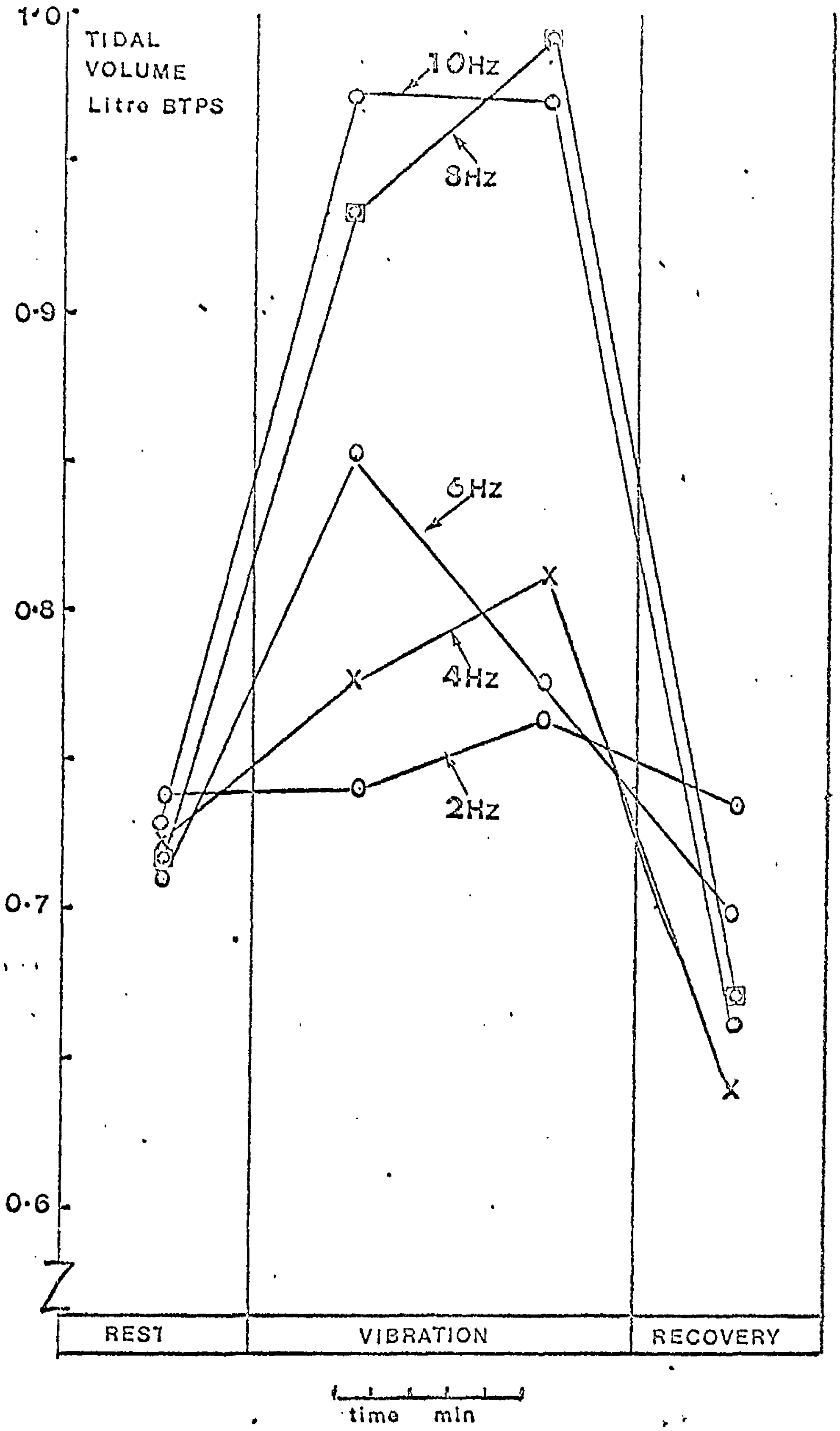


Figure 4. 5 Mean values of tidal volume during exposure to constant amplitude vibration.

carbon dioxide tension obtained during recovery from the experimental vibration are also presented in Table 4.6. The mean changes induced in the end-expiratory carbon dioxide tension by vibration at frequencies of 2 - 10 Hz with subjects restrained and unrestrained in the seat are shown graphically in figure 4.6. It may be seen that with exposure to vibration at frequencies of 2 and 4 Hz there were no marked changes in the values of end expiratory carbon dioxide tension during the vibration period, from those values obtained during the period of rest. With exposure to vibrations at frequencies of 6, 8 and 10 Hz, however, there was a reduction in the values of end tidal carbon dioxide tension during the vibration period and this reduction was maintained until the vibration ceased. The effect was greatest with vibrations at the higher frequencies (8 Hz and 10 Hz) and in three subjects moderately severe symptoms of hypocapnia occurred during exposure to vibration at a frequency of 10 Hz. In those subjects who exhibited symptoms of hypocapnia the end tidal carbon dioxide tensions fell from mean values of 38 - 40 mm Hg obtained during rest to values of 28 - 32 mm Hg during the experimental vibration period.

During those experimental vibration exposures in which a fall in end tidal carbon dioxide tension occurred, the effect was evident within about 15 to 20 seconds after the start of vibration. Within one minute of vibration exposure the end tidal carbon dioxide tension reached a new level and this was maintained fairly

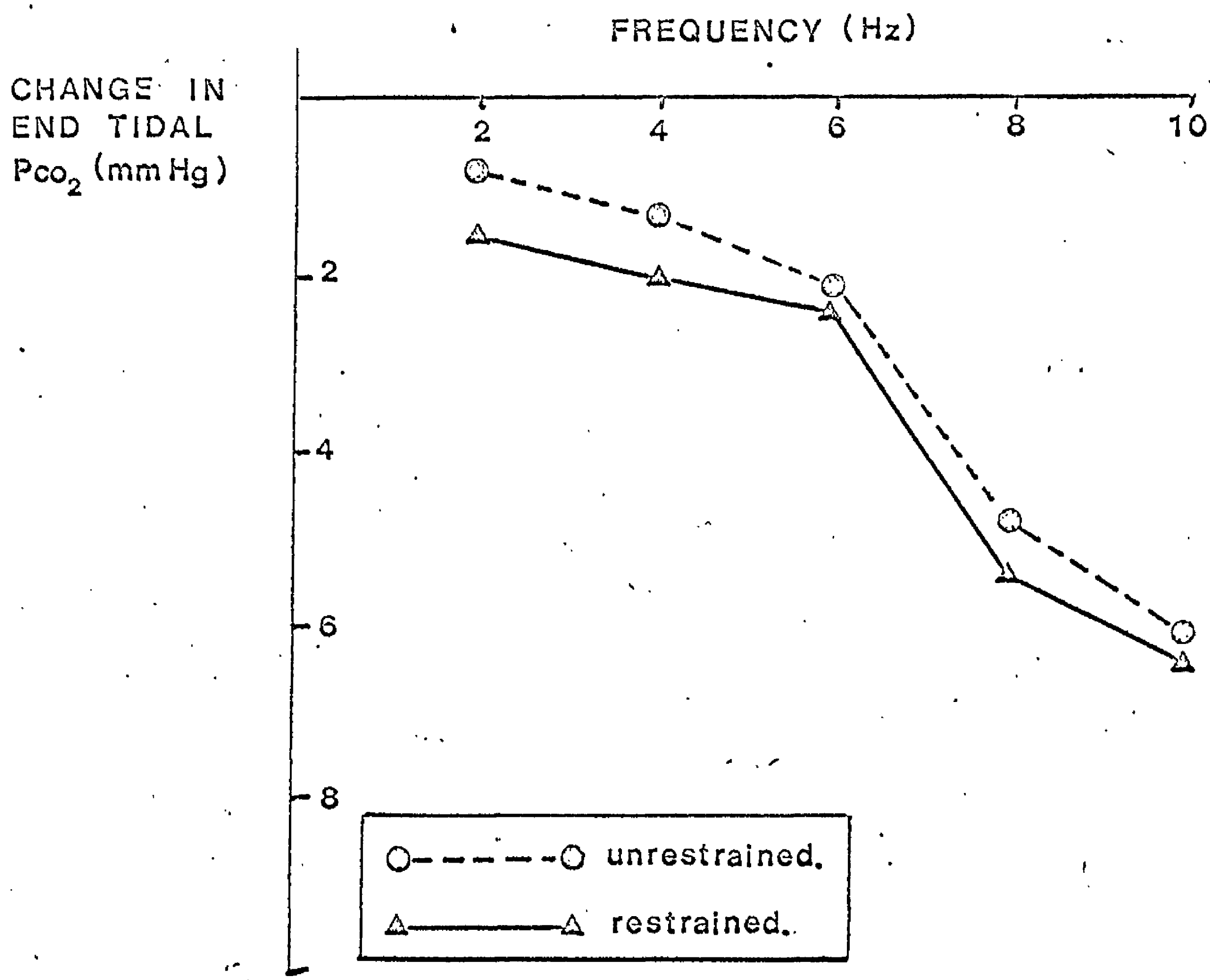


Figure 4. 6 Changes in end-tidal carbon dioxide tension during exposure to constant amplitude vibration.

constant throughout the period of vibration. On cessation of vibration, there was a rapid increase in end tidal carbon dioxide tension with a further more gradual increase towards pre-vibration control values over the next 2 - 3 minutes. A return of end tidal carbon dioxide tension to values which existed prior to the onset of vibrations was complete in most cases within 3 - 4 minutes of stopping vibration. These effects of whole-body vibration on end tidal carbon dioxide tension are illustrated in figure 4.7. This figure shows a record of end tidal carbon dioxide concentration obtained during an experimental run in which the subject was exposed for a short period to high intensity experimental vibration (frequency 8 Hz). The rapid decline in values of end tidal carbon dioxide concentration following the onset of vibration and the first rapid then gradual return to pre-vibration control values may be seen from the experimental record shown in figure 4.7.

(f) Metabolic oxygen uptake

The results of the measurements of metabolic oxygen uptake which were made during this series of experiments are presented in Table 4.7, for nine subjects who were restrained and unrestrained in the vibration seat and exposed to vibrations at frequencies of 2, 4, 6, 8 and 10 Hz.

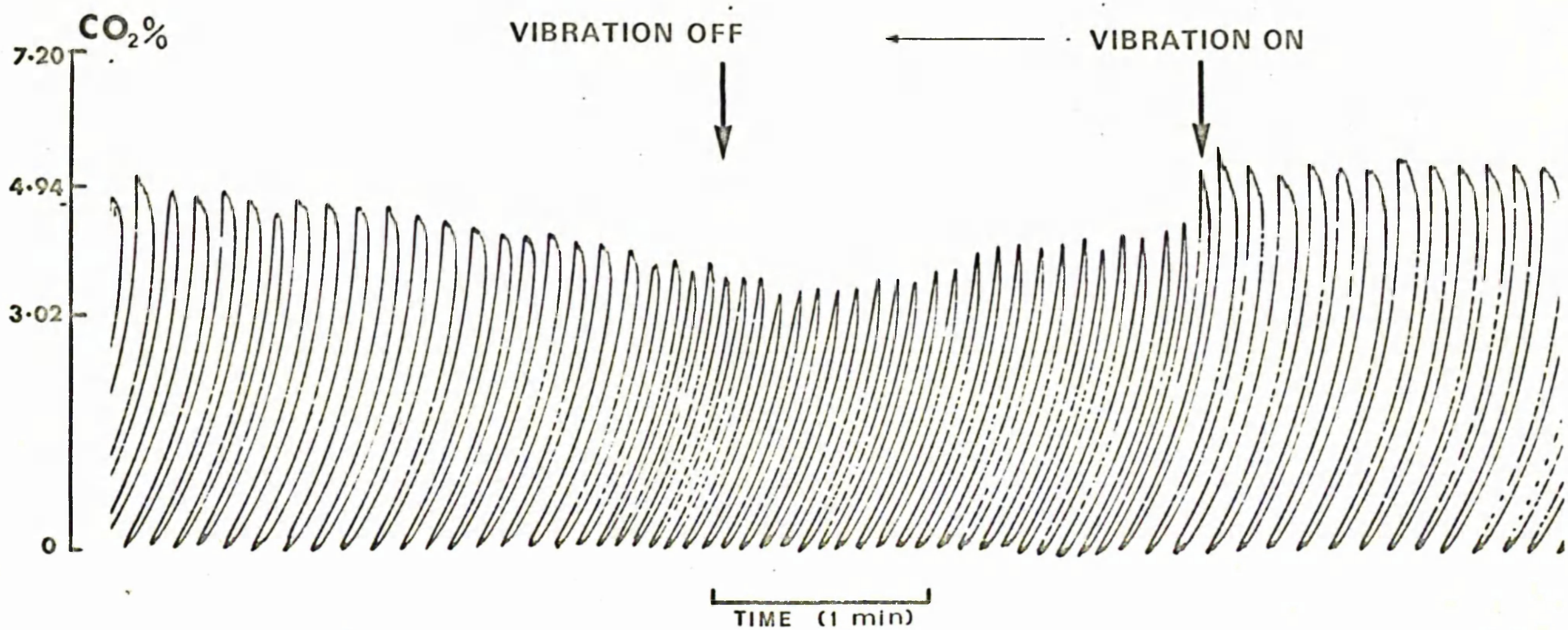


Figure 4. 7 Behaviour of end-tidal carbon dioxide concentration during exposure to constant amplitude vibration.

Table 4.7 Effect of whole-body vibration on metabolic oxygen consumption. Nine subjects, exposed to vibration at frequencies of 2 - 10 Hz in the restrained and unrestrained conditions

Frequency of vibration (Hz)	Mean values of oxygen consumption (L/min STPD) in the following condition			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
	RESTRAINED			
2	0.299	0.301	0.270	0.302
4	0.278	0.274	0.271	0.274
6	0.280	0.388	0.390	0.272
8	0.317	0.472	0.476	0.292
10	0.277	0.525	0.505	0.260
	UNRESTRAINED			
2	0.313	0.283	0.278	0.272
4	0.287	0.270	0.274	0.261
6	0.282	0.372	0.332	0.269
8	0.302	0.476	0.509	0.272
10	0.278	0.518	0.531	0.274

It may be seen from Table 4.7 that with the subject both in the restrained and unrestrained conditions in the vibrating seat there was a marked increase in the mean values of oxygen consumption during exposure to vibration at frequencies of 6, 8 and 10 Hz. It may also be seen that mean values of oxygen consumption increased with increasing intensities of vibration exposure and that the greatest increase occurred with exposure of the subject to vibration at the highest frequency (10 Hz).used in the study.

With exposure of the subject to whole-body vibration at frequencies of 2 Hz and 4 Hz there were no significant increases in values of metabolic oxygen consumption in the subject over those obtained with him at rest. With vibration exposures at frequencies of 6 Hz, 8 Hz and 10 Hz the mean values of oxygen consumption were significantly greater than those obtained at rest ($P = 0.001$). Analysis has shown, also, that there were no significant differences in values of metabolic oxygen consumption in both experimental conditions (where the subject was restrained by a seat harness and where he was unrestrained in the vibrating seat). In those experimental conditions in which an increase in metabolic oxygen consumption occurred this increase was sustained almost unchanged throughout the period of vibration exposure. At the termination of vibration, the mean values for metabolic oxygen consumption fell below those measured during the resting period prior to vibration. This effect was highly significant following exposures to vibration at frequencies of 6, 8 and 10 Hz. The mean changes in the values of metabolic oxygen consumption which occurred in this part of the investigation are summarised in figures 4.8 and 4.9 for nine subjects exposed to various conditions of whole body vibration.

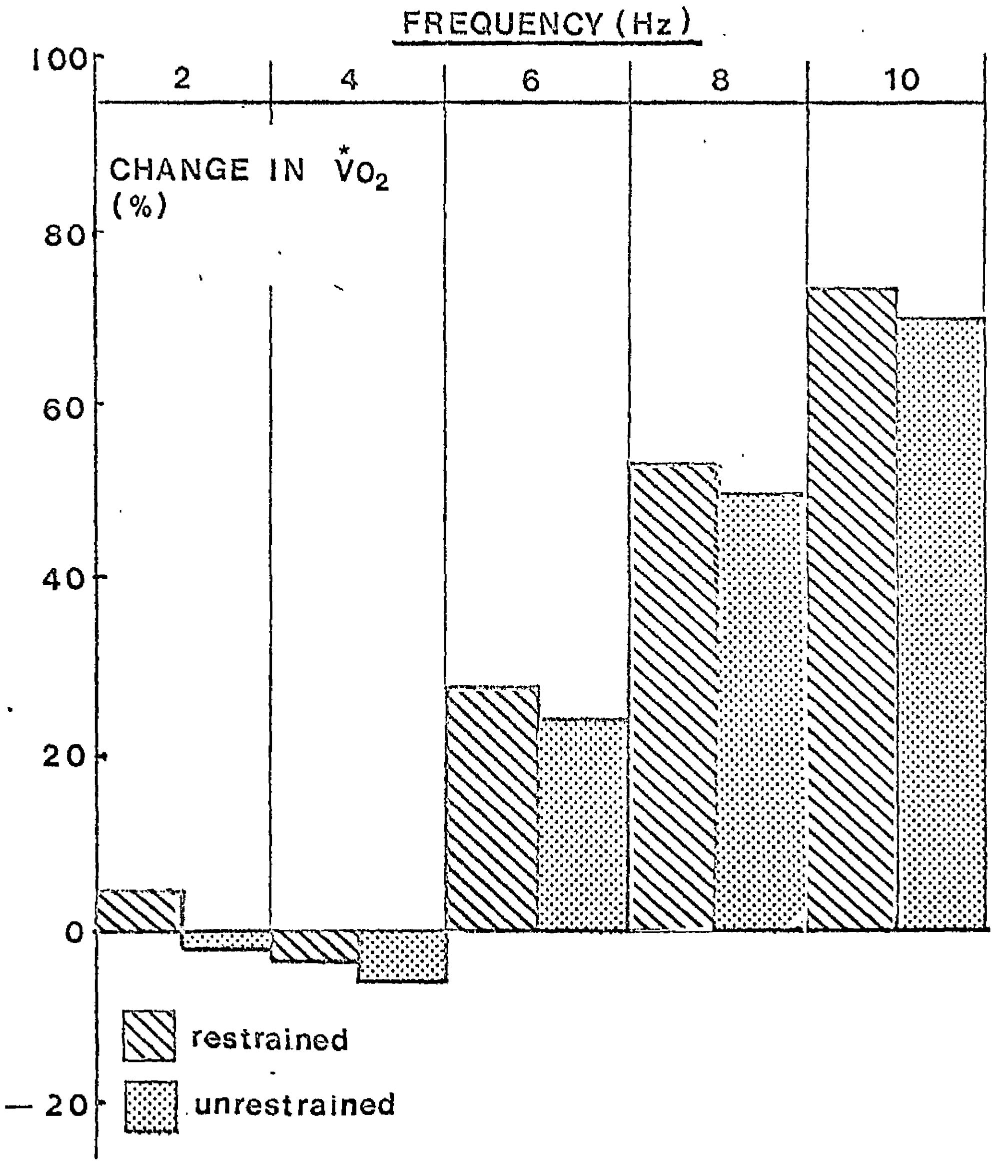


Figure 4. 8 Changes in metabolic oxygen consumption during constant amplitude vibration.

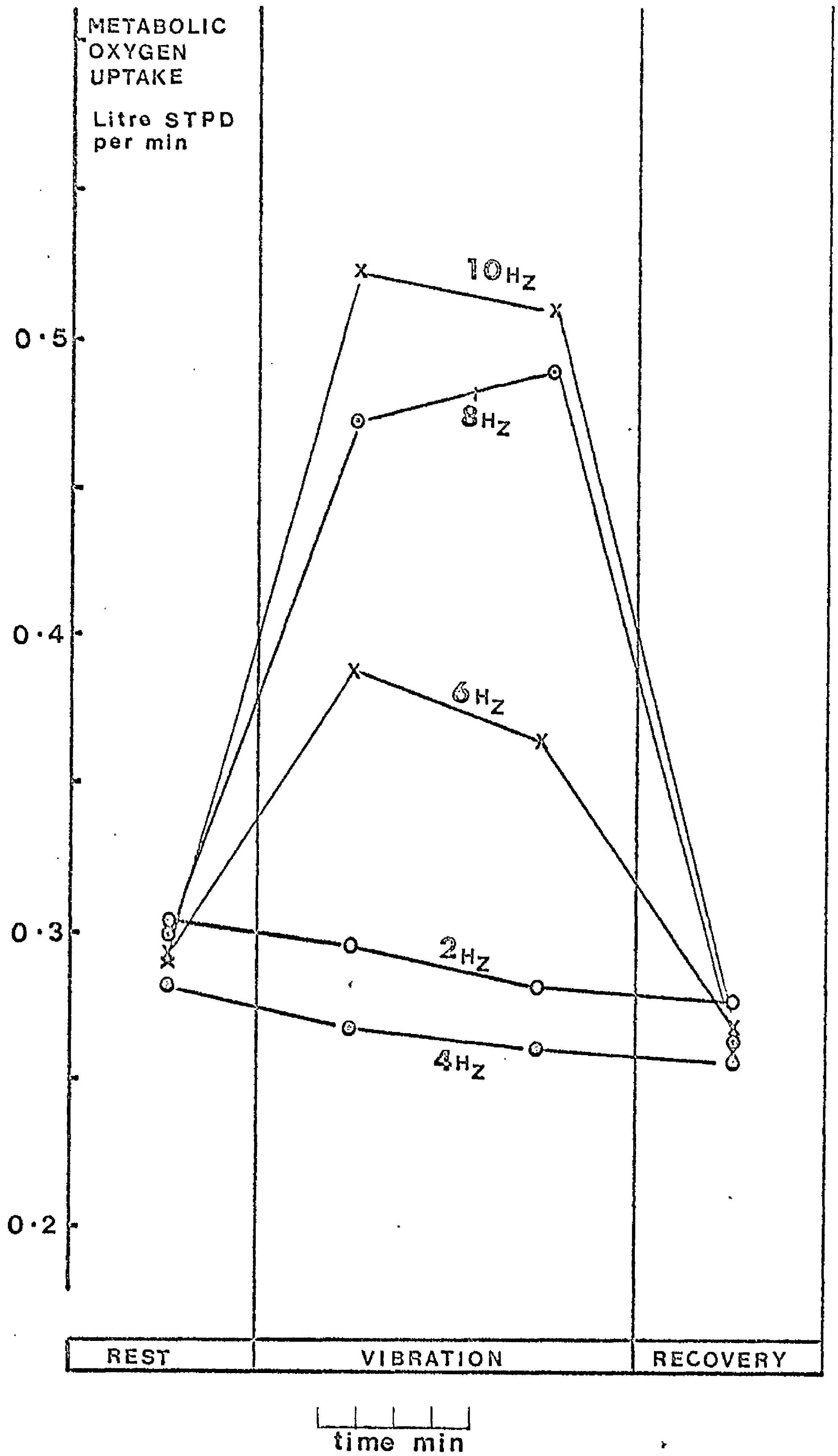


Figure 4. 9 Mean values of metabolic oxygen uptake during constant amplitude vibration.

In order to allow a comparison to be made of the metabolic activity associated with exposure of the subject to whole-body vibration with that associated with flying various types of aircraft, values of metabolic oxygen consumption have been re-calculated in the units kcal/m^2hr and these are shown in Table 4.8. It may be seen from Table 4.8 that after exposure of the subject to vibration at a frequency of 6 Hz for a period of five minutes there was an increase in the value of energy expenditure from 46.7 kcal/m^2hr obtained at rest to 59.3 kcal/m^2hr during vibration. With exposure to vibration at a frequency of 8 Hz this value increased from 47.3 kcal/m^2hr obtained at rest to 75.8 kcal/m^2hr during vibration and at a frequency of 10 Hz the value increased from 46.5 kcal/m^2hr during rest to 82.5 kcal/m^2hr during vibration exposure. At the higher frequencies in the range studied, the values of energy expenditure obtained in the seated subject during vibration were similar in magnitude to those obtained in the pilot during some of the most intensive phases of flight (e.g. instrument approaches, combat and emergency situations) in fixed wing aircraft and during hovering, ascent and landing in helicopters.

Table 4.8 Effects of whole-body vibration at a constant displacement amplitude on metabolic energy expenditure. Mean values for nine subjects exposed to various conditions of vibration

Frequency of vibration (Hz)	Mean value of metabolic energy expenditure (kcal/m hr) during:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
2	47.4	46.8	43.9	44.2
4	44.6	42.6	41.8	40.9
6	46.7	59.3	58.8	42.6
8	47.4	75.8	78.7	43.2
10	46.5	82.5	81.8	40.6

(g) Carbon dioxide output

The results of measurements of carbon dioxide output which were obtained in this series of experiments are presented in Table 4.9 for nine subjects, restrained and unrestrained in the vibrating seat. It may be seen by reference to Table 4.9 that with the subject both restrained and unrestrained in the vibrating seat there was a marked increase in the mean values of carbon dioxide production during vibration exposures at frequencies of 6, 8 and 10 Hz. The mean values of carbon dioxide production during exposure to vibrations at frequencies of 2 Hz and 4 Hz were not significantly different from those obtained with the subject at rest. It may be noted that in those conditions of

Table 4.9 Effect of whole-body vibration on carbon dioxide output. Mean values for nine subjects exposed to vibration at frequencies 2 - 10 Hz in the restrained and unrestrained condition

Frequency of vibration (Hz)	Mean values of carbon dioxide output (L/min STPD) in the following conditions:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	0.263	0.259	0.024	0.250
4	0.258	0.258	0.240	0.225
6	0.260	0.353	0.320	0.210
8	0.261	0.489	0.491	0.224
10	0.263	0.523	0.541	0.230
		UNRESTRAINED		
2	0.265	0.270	0.240	0.231
4	0.251	0.274	0.242	0.209
6	0.271	0.350	0.300	0.233
8	0.266	0.470	0.490	0.234
10	0.253	0.527	0.513	0.232

the experiment in which a marked increase in carbon dioxide production occurred during the vibration exposure, that increase was related to the intensity of the vibration and the highest values were obtained with exposure to vibration at a frequency of 10 Hz.

The values of carbon dioxide obtained with vibration exposures at frequencies of 6, 8 and 10 Hz were significantly greater than those obtained during the resting control period (P = 0.001). The values obtained with exposures to vibration at frequencies of 2 and 4 Hz were not, however, significantly greater than those obtained during the resting period. Furthermore, with those exposures to vibration where an increase in carbon dioxide production occurred that increase was sustained until the vibration ceased after which there was a significant (P = 0.01) fall in values during the recovery phase of the experiment, below those obtained with the subject at rest.

(h) Respiratory Exchange Ratio

The results for measurement of the Respiratory Exchange Ratio obtained in this series of experiments are presented in Table 4.10 for nine subjects exposed to vibration at frequencies of 2 - 10 Hz, both restrained and unrestrained by harness in the vibrating seat. It may be seen by reference to Table 4.10 that in both conditions of the experiment (i.e. with subject restrained and unrestrained) there was an increase in mean values of Respiratory Exchange Ratio with the subject exposed to vibration at frequencies of 6, 8 and 10 Hz, although with exposure to vibration at frequencies of 2 and 4 Hz the Ratio remained virtually unchanged. It may also be seen that with exposure to vibration at the highest frequency used (10 Hz) the mean value of the Ratio increased above unity. The values of Respiratory Exchange Ratio found during exposure to vibration at frequencies of 6, 8 and 10 Hz were in each case

Table 4.10 Effects of whole-body vibration on the Respiratory Exchange Ratio. Mean values for nine subjects exposed to vibration at frequencies of 2 - 10 Hz in the restrained and unrestrained condition

Frequency of vibration (Hz)	Mean values of Respiratory Exchange Ratio in the following conditions:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	0.927	0.915	0.898	0.884
4	0.870	0.942	0.874	0.827
6	0.938	1.004	0.940	0.841
8	0.820	0.943	0.974	0.760
10	0.873	1.004	1.021	0.889
		UNRESTRAINED		
2	0.848	0.874	0.833	0.813
4	0.872	0.975	0.874	0.800
6	0.845	0.921	0.913	0.746
8	0.854	0.981	0.970	0.804
10	0.866	1.008	1.020	0.825

significantly greater than those obtained during the resting period ($P = 0.001$) whilst with vibration exposures at frequencies of 2 and 4 Hz the difference in values obtained in the period of vibration were not significantly different from those obtained with the subject at rest. In the conditions in which the Ratio increased during the vibration exposure, this increase was sustained throughout the period of vibration and on cessation of the vibration fell significantly below the value obtained with the subject at rest. The differences in the behaviour of the Respiratory Exchange Ratio were not significant between the condition in which the subject was restrained and unrestrained in the vibration seat.

(i) Symptoms arising during vibration

At the end of each experimental run, the subject was asked to complete a questionnaire listing the symptoms he had experienced during each vibration exposure. This questionnaire asked specifically for details of general comfort during the vibration run, any discomfort arising in the chest, abdomen, back, head and neck, pelvis or in any other anatomical site. In this part of the investigation no attempt was made to quantify the intensity of the discomfort, although a quantitative approach was used in a subsequent experiment which is reported in a later chapter of this thesis. The number of reports of symptoms arising during a total of 90 experimental vibration exposures are summarised in Tables 4.11 and 4.12 for nine subjects, each of whom experienced vibration at frequencies of 2, 4, 6 and 8 Hz for a period of 10 minutes. The results presented in Table 4.11 show the symptoms reported by subjects during the runs in which they were fully restrained in the seat and in Table 4.12 the results are given for the condition where subjects were unrestrained in the seat.

Table 4.11 Summary of symptoms reported during whole-body vibration at frequencies of 2 - 10 Hz with the subject restrained in the vibration seat (Nine subjects) (Each + represents one report)

Symptom	Frequency of vibration (Hz)				
	2	4	6	8	10
			RESTRAINED		
General discomfort			++++	++++++	+++++++++
Pain or discomfort in chest		+	++++	++++++	++++++++
Pain or discomfort in abdomen			++	++	++++
Pain or discomfort in back				++	++
Pain or discomfort in head and neck			+		+
Pain or discomfort in pelvis			++		

Table 4.12 Summary of symptoms reported during whole-body vibration at frequencies of 2 - 10 Hz with subject unrestrained in the vibrating seat (Nine subjects) (Each + represents one report)

Symptom	Frequency of vibration (Hz) 2	4	6	8	10
			UNRESTRAINED		
General discomfort		+	++	+++++	++++++++
Pain or discomfort in chest		+	+++	+++++	+++++++
Pain or discomfort in abdomen			++	++	+++
Pain or discomfort in back					+
Pain or discomfort in head and neck			++		+
Pain or discomfort in pelvis			+		

It may be seen by reference to Tables 4.11 and 4.12 that in general, most subjects found vibration uncomfortable at frequencies of 6, 8 and 10 Hz both when restrained and unrestrained in the vibrating seat. The tables show quite clearly that a greater degree of discomfort in both conditions of restraint was associated with vibration at the higher rather than at the lower levels of intensity. Thus, with exposure to vibration at a frequency of 2 Hz there were no reports of discomfort with the subject either restrained or unrestrained in the seat. Indeed, a number of subjects found exposure to vibration at this frequency actually pleasant and some subjects experienced a soporific sensation.

With exposure to vibration at a frequency of 4 Hz (intensity = $\pm$ 0.21 Gz) there was only one report of discomfort and this took the form of mild fluttering of pectoral muscles during the later minutes of the vibration period. With vibration exposures at a frequency of 6 Hz (intensity = $\pm$ 0.49 Gz) the number of reports of discomfort both in the restrained and unrestrained conditions showed a marked increase. It is known that at this frequency there is a dominant mode of resonance in the body and a number of subjects complained of superficial chest discomfort (probably associated with resonance of the pectoral muscle mass), with mild discomfort in the upper right quadrant of the abdomen (probably due to resonance of liver and other viscera) and in the shoulders, head and neck. There were also two reports of discomfort in the area of the pelvis at this frequency of vibration.

With exposure to vibration at a frequency of 8 Hz (intensity = $\pm$ 0.89 Gz) there was a very marked increase in the number of reports of general discomfort both with the subject restrained and unrestrained in the vibrating seat. The predominant anatomical sites for the pain experienced during this vibration exposure were the subcostal and substernal areas. Thus, five subjects who were unrestrained and six subjects who were restrained in the vibrating seat complained of severe retrosternal and subcostal pain which arose early in the period of vibration, increased in severity and finally radiated to the neck and right shoulder. It was observed by one subject that this pain could be relieved to a certain extent by applying pressure by hand to the affected area although all subjects were thereafter strictly instructed to make no attempt to devise means of relieving their discomfort. Two subjects reported pain in the upper abdomen both when restrained and unrestrained in the vibrating seat. This pain was described in each case as deep seated, dull in nature and confined to the upper right quadrant of the abdomen. Two subjects reported discomfort in the lumbar area of the spine after about 4 - 5 minutes of vibration at a frequency of 8 Hz.

By far the greatest number of reports of acute discomfort during the vibration period were obtained with exposure of the subject to vibration at a frequency of 10 Hz (vibration intensity =

$\pm$ 1.43 Gz). The acute discomfort reported during exposure to vibration at this frequency occurred with the subject restrained and unrestrained in the vibrating seat. During vibration at this frequency almost every experimental subject complained of near intolerable discomfort which began in the first few seconds after the start of vibration and either remained unchanged or increased in intensity as the vibration exposure progressed. The majority of subjects complained of very severe pain in the chest which had similar characteristics to that experienced during exposure to vibration at 8 Hz but differed slightly in its radiation characteristics (radiation mainly to the upper back region) and was of much greater severity. During one experimental procedure, the run was stopped because the subject experienced intolerable discomfort in the chest after 4 minutes exposure at this frequency. This run was repeated at a later date and the data obtained during the first vibration run were not used in the series. With vibration exposure at a frequency of 10 Hz, abdominal discomfort was also reported but was less commanding than the acute chest pain. Two subjects reported acute discomfort in the head due to excessive movement which occurred in the later minutes of the vibration exposure.

The symptoms experienced by the subjects in the present study were broadly similar to those reported by Guignard (1964) who exposed his subjects to vibration at frequencies of 2 - 10 Hz. It is believed that in the present study most of the symptoms described by the experimental subjects were mechanical in origin and associated with resonance effects in the torso and pectoral girdle.

In summary, it may be stated that the results of this experiment show that exposure to constant amplitude whole-body vibration in the frequency range 2 - 10 Hz induces marked discomfort in the subject at certain frequencies. This discomfort arises mainly in chest and abdomen although to a lesser extent may occur in the pelvis, head, shoulders and neck. The severity of the discomfort is apparently related to the intensity of the imposed vibration and ranges from either total lack of, or minor discomfort at frequencies of 2 and 4 Hz (intensities of vibration $\pm$ 0.05 Gz and $\pm$ 0.21 Gz respectively) to frankly intolerable pain at vibration frequencies of 8 and 10 Hz (intensities of vibration $\pm$ 0.89 Gz and $\pm$ 1.43 Gz respectively). It has also been demonstrated that the incidence and magnitude of discomfort associated with whole-body vibration within the range of frequencies studied occurs both with the subject restrained and unrestrained by a harness in the vibrating seat.

(j) Cardiac frequency

Previous studies on the respiratory effects of whole-body vibration, notably those of Hood et al (1966) suggest that vigorous mechanical movement of the whole body and particularly of the extremities acts as a "mild circulatory stress". Since very few investigators have studied these changes in detail the main effect of whole-body vibration on the circulatory system which is reported in the literature relates to the cardiac frequency. In the present series of experiments the results of measuring cardiac frequency during each vibration exposure with subjects restrained and unrestrained in the vibrating seat are presented in Table 4.13.

It may be seen by reference to Table 4.13 that with the subject both restrained and unrestrained in the vibrating seat there was an increase in cardiac frequency during vibration exposures at frequencies of 6, 8 and 10 Hz, the greatest change occurring with vibration at a frequency of 10 Hz. The mean values of cardiac frequency observed during the exposure to vibration at frequencies of 6, 8 and 10 Hz were significantly greater than those obtained with the subject at rest. ($P = 0.001$). Furthermore the observed increase was greater after 5 minutes of vibration and declined towards the end of the vibration period. This effect was significant at the 1% level. In those vibration exposures where an increase in cardiac frequency occurred, cessation of the vibration caused a fall in values below those recorded during the control rest period. This effect was highly significant ($P = 0.001$). The effects of exposure to vibration at frequencies of 6, 8 and 10 Hz on heart

Table 4.13 Effects of whole-body vibration on cardiac frequency. Mean values for nine subjects exposed to vibration at frequencies of 2 - 10 Hz in the restrained and unrestrained conditions

Frequency of vibration (Hz)	Mean values of cardiac frequency (beats per minute) in the following conditions:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	84.1	82.5	81.3	80.1
4	79.1	78.0	75.5	76.7
6	81.2	86.3	78.9	77.5
8	84.6	89.2	85.2	79.5
10	84.8	97.0	92.3	82.6
		UNRESTRAINED		
2	82.2	84.6	80.1	79.5
4	81.0	79.5	80.2	77.4
6	83.4	86.0	79.2	78.4
8	85.0	89.3	84.7	80.0
10	84.0	96.2	92.2	80.1

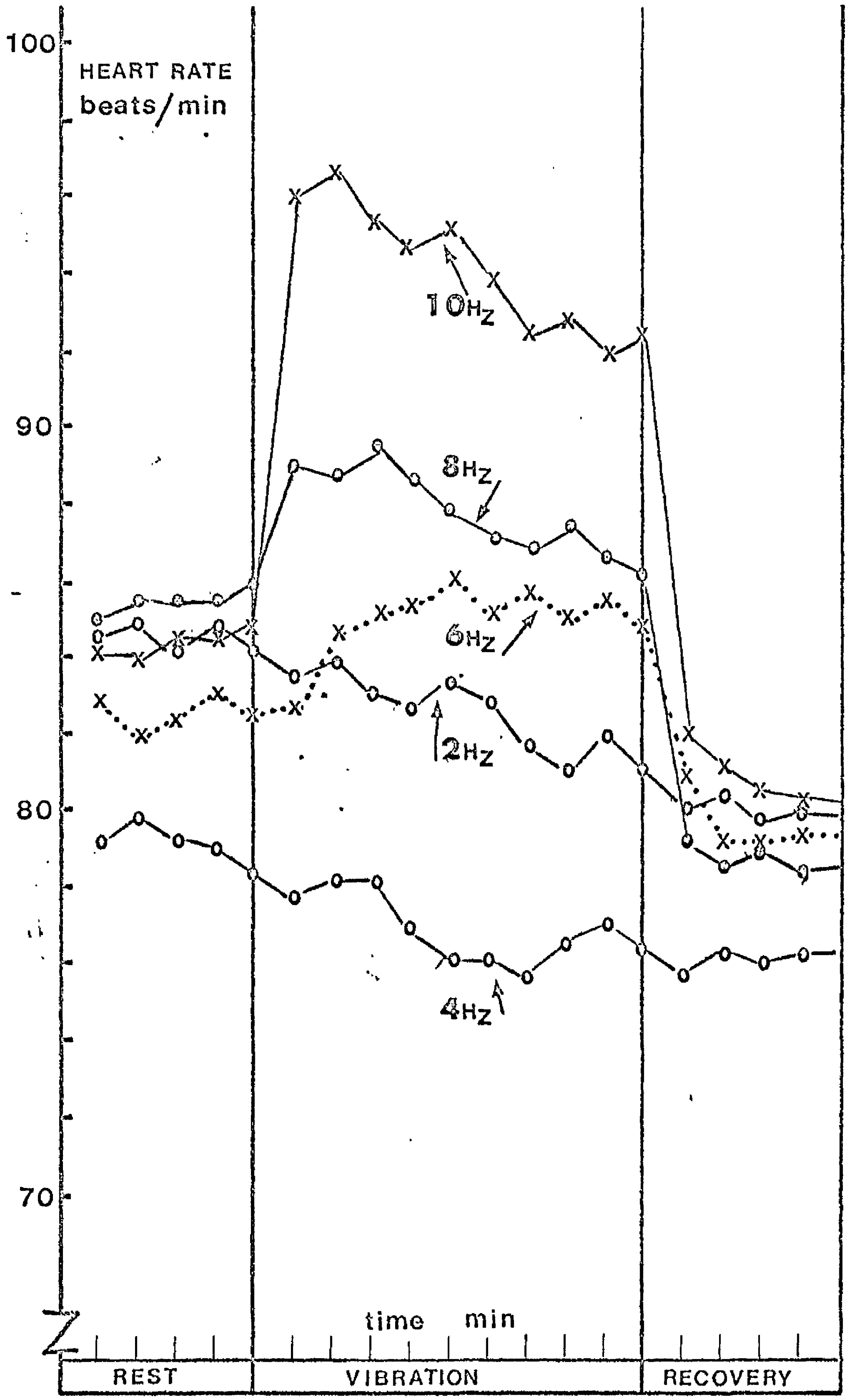


Figure 4. 10 Cardiac frequency during exposure to constant amplitude vibration.

rate occurred in the two experimental conditions, i.e. with the subject restrained and unrestrained in the vibrating seat ($P = 0.001$). The mean changes in heart rate observed for each minute with the subject at rest, during exposure to vibration at frequencies of 2 - 10 Hz and during recovery are shown in figure 4.10. In this graph the values obtained with the subject restrained in the vibrating seat have been pooled with those obtained with the subject unrestrained.

(k) Movement of muscle masses during vibration

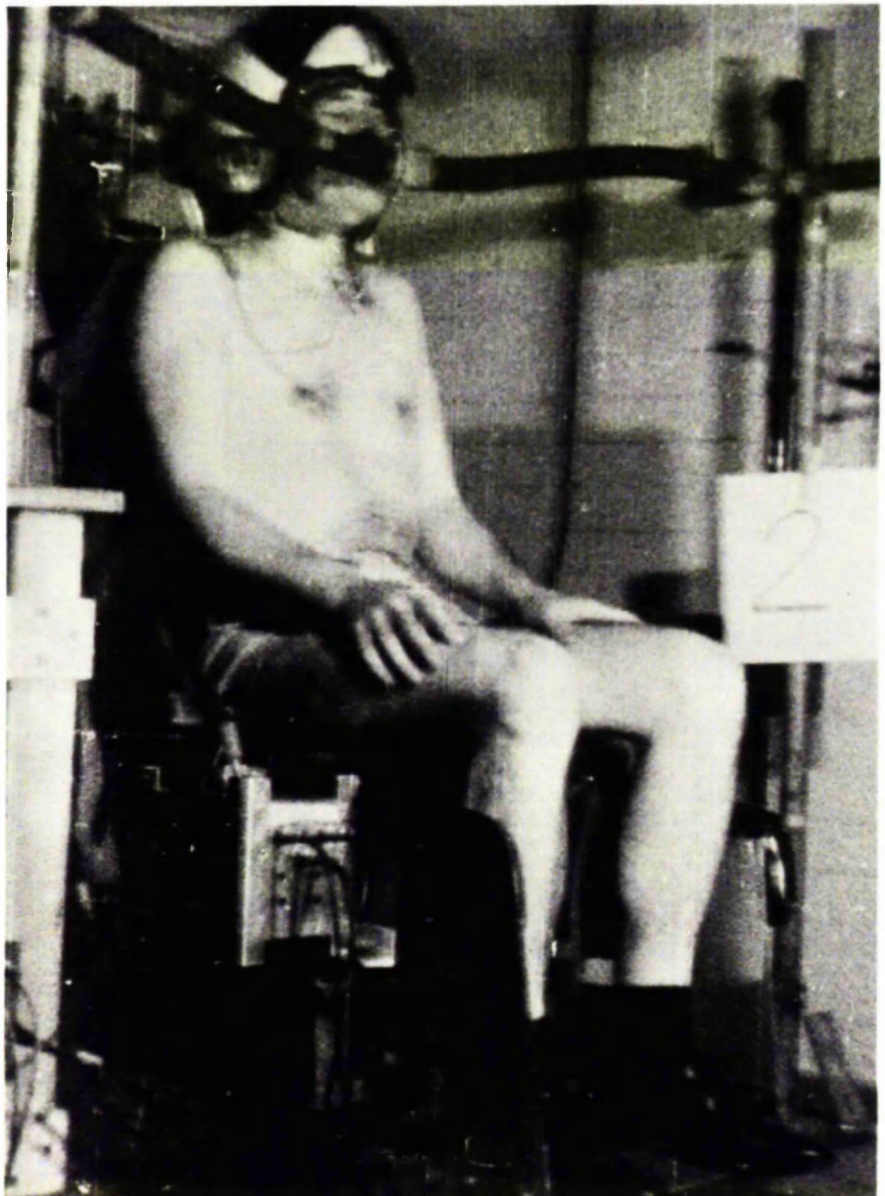
The response of various muscle masses of the body during exposure to constant amplitude vibration at frequencies of 2, 4, 6, 8 and 10 Hz was examined during this series of experiments using high speed cinephotography. Observations were made on the response of various groups of muscles in the body to the experimental vibration by running the exposed cine film through an editing viewer at a speed of 16 frames per second and where appropriate by examining each separate frame.

The observations carried out in this part of the experiment show that when the subject was exposed to vibration at a frequency of 2 Hz the behaviour of muscle masses was little different from that observed during the period of rest prior to vibration. With vibrations at a frequency of 4 Hz there was marked movement of the pectoral muscles in an upwards and downwards direction at approximately the same frequency of motion as the forcing vibration.

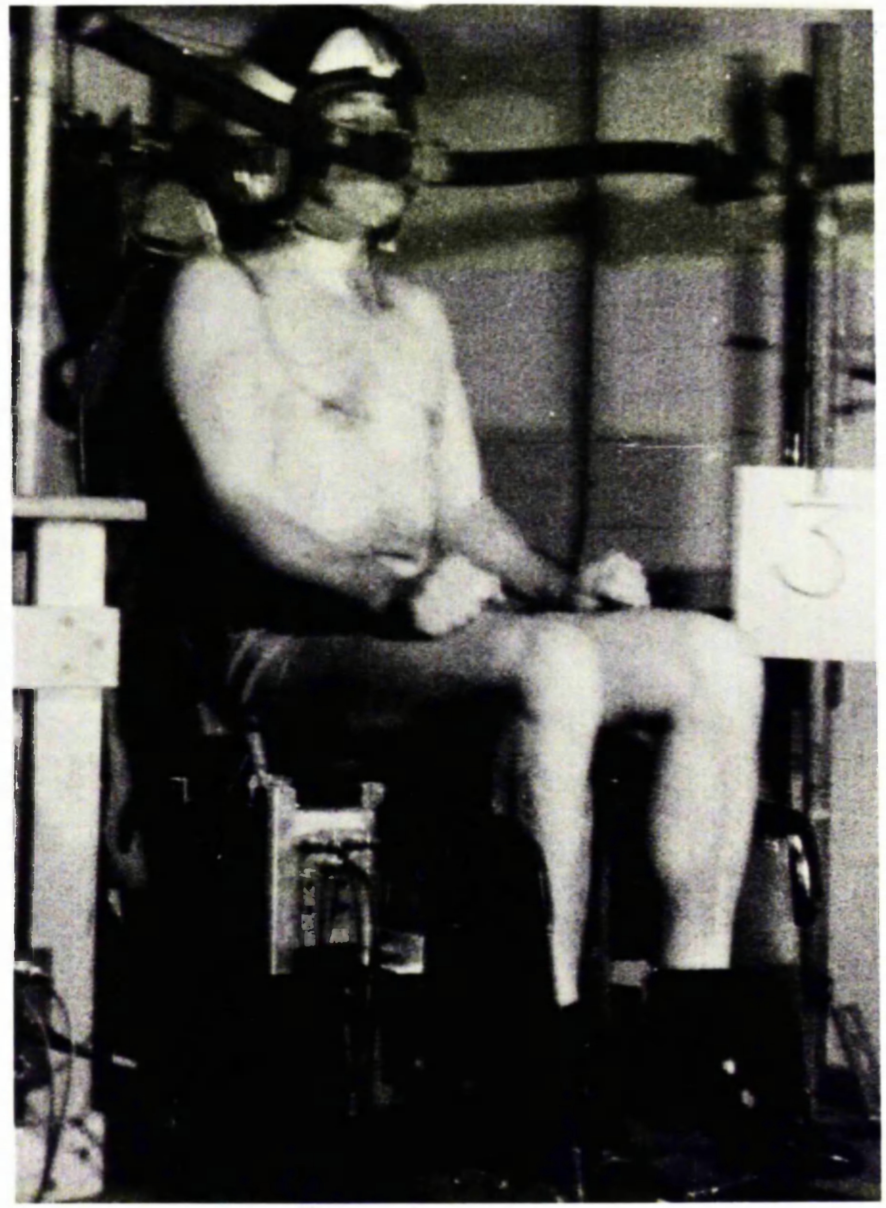
There was, however, no attempt on the part of the experimental subject to tense these muscles in order to reduce the degree of movement. Similar movement of musculature in the calves and upper region of the thigh was observed and the nature of this movement remained essentially unchanged throughout the period of vibration. An upwards and downwards movement of the shoulder girdle was also observed during exposure to vibration at a frequency of 4 Hz and no attempt was made by the subject to modify or attenuate this motion.

During exposure of the experimental subject to vibration at a frequency of 6 Hz a number of interesting phenomena were observed on analysing the high speed cine film. At this frequency, vibration caused almost immediate and simultaneous movement of muscle masses in the calves and upper region of the thigh. These movements were large in magnitude and at approximately the same frequency as the forcing vibration and were probably due to resonance effects at this frequency. Within two to three seconds of the start of this muscle motion, the experimental subject responded by tensing the appropriate muscle group for a period of about three to four seconds during which the movement of the muscle mass was visibly reduced. At the end of this period of muscle tensing, there was obvious relaxation on the part of the subject and the muscle mass returned to a motion at about the same frequency as the forcing vibration. At the end of approximately 5 seconds of relaxation the muscle tensing procedure was once more adopted by the experimental subject. Throughout the period of observation the subject alternately tensed and relaxed musculature probably in an attempt to attenuate the excessive movement occasioned by the forcing vibration. A similar phenomenon was observed at this frequency of vibration for the large mass of pectoral muscles which alternately relaxed and tensed during the period of vibration.

Similar observations were made during exposure of the subject to vibration at a frequency of 8 Hz. With this condition the groups of muscle masses involved included calf and upper thigh masses, pectoral muscles, biceps muscles and strap muscles of the neck. Each of these muscle groups exhibited a marked degree of movement immediately after the vibration was started and this was followed within a few seconds by vigorous tensing of the appropriate muscle mass and consequent reduction in movement. Throughout the period of vibration in which observations were carried out, the phenomenon of alternate tensing and relaxation of musculature was clearly visible. In figure 4.11 two frames of the high speed cine film have been reproduced. In one frame, the characteristic phase of muscle relaxation is shown during exposure of the subject to vibration at a frequency of 8 Hz. In the adjacent photograph, tensing of various groups of muscles may



Frame A



Frame B

Figure 4. 11 Single frames of high speed film showing the phase of muscular relaxation (A) and phase of muscular tensing (B) during vibration at frequency, 8Hz.

be seen as a characteristic response to vibration at the same frequency and intensity.

Observations of the high speed cine film taken during exposure of the subject to vibration at a frequency of 10 Hz show that a very large number of muscle groups were involved in the tensing - relaxation phenomenon observed at other frequencies of vibration. In this experimental condition it was noted that in addition to tensing of muscles of upper and lower limbs and the chest, there was also marked contraction of abdominal musculature. Also, it was noted that with the onset of high intensity vibration at this frequency the subject tried to adopt an arched posture by contraction of lumbar and dorsal musculature presumably in an attempt to modify or attenuate transmission of vibration to more vulnerable parts of the body. It was noted that at this frequency of vibration the periods of sustained muscular contraction were longer than those observed during vibrations of lesser intensity, and in these circumstances the periods of muscular relaxation were consequently reduced. The response of muscle groups to vibration exposure at various frequencies and intensities, was the same for both conditions of the experiment (i.e. where the subject was restrained or unrestrained by harness in the vibrating seat).

4.4 Discussion

The experiments which have been described in this chapter have demonstrated very clearly that at certain frequencies constant amplitude whole-body vibration causes an increase in pulmonary ventilation in the experimental subject. Thus, it has been shown that with vibration exposure at forcing frequencies of 6, 8 and 10 Hz there was a marked increase in mean values of minute volume ventilation, tidal volume and respiratory frequency with the maximum changes in these values occurring at the highest forcing frequency (10Hz) used in this study. The results indicate that at those frequencies of vibration pulmonary ventilation reached maximum values aftdr about 5 minutes of vibration and thereafter, declined in magnitude towards the end of the vibration period. The results show that after five minutes of vibration at frequencies of 6, 8 and 10 Hz there was an increase in minute volume ventilation of 35%, 63% and 80% respectively over values obtained with the subject at rest. After ten minutes of vibration at these frequencies the increase in minute volume was reduced to 18.5%, 61.5% and 67% of resting control values at 6, 8 and 10 Hz respectively. The magnitude of the changes in minute volume ventilation observed during this series of experiments was similar to that obtained by previous workers (Ernsting, 1961; Hoover & Ashe, 1962) who exposed their subjects to constant amplitude whole-body vibration. In the present study it was found that the increase in minute volume ventilation was brought about by increase in both tidal volume and respiratory frequency during the period of vibration. This finding is in agreement with that of Hoover & Ashe, 1962 but differs from that of Ernsting (1961) who reported that the increase in minute volume ventilation obtained in his subjects during the vibration period was produced largely by an increase in tidal volume. In the present study, there was a moderate increase in tidal volume after the onset of vibration at frequencies of 6, 8 and 10 Hz, and this increase was sustained almost unchanged throughout the entire period of vibration. It is believed that at least part of the increase in tidal volume can be explained on the basis of superimposition of oscillations upon the respiratory flow at the forcing frequency. In his investigations, Ernsting (1961) showed that such oscillatory volume of gas resulted from involuntary movement of viscera in and out of the thoracic cage with each cycle of vibration, thus driving gas into and out of the lungs. He demonstrated however that the superimposed oscillatory volume of gas during the vibration period was for the most part effective only in ventilating the functional dead space and could not therefore be responsible for the hyper-ventilation which he observed in his experiments. This finding was supported by the studies of Hoover & Ashe (1962). By contrast, the changes in respiratory frequency induced by whole-body vibration in the present study match the changes observed in minute volume ventilation. Thus, the increase in respiratory frequency which occurred during exposure of the subject to certain conditions of whole-body vibration, reached a maximum value after about five minutes of vibration and thereafter declined in value towards the end of the total period of vibration exposure. This observation strongly suggests that the change in respiratory frequency was the predominant factor controlling the change in pulmonary ventilation observed during the vibration period, although an increase in tidal volume undoubtedly contributed to this phenomenon but to a lesser extent.

In the present context, one of the most important results obtained in this series of experiments concerns the relative increase in pulmonary ventilation produced by a given combination of frequency and amplitude of vibration which was greater than the corresponding increase in metabolic oxygen uptake. This provides evidence that with exposure to vibration at frequencies of 6, 8 and 10 Hz true hyper-ventilation was induced in the experimental subject and this is supported by the finding of a greater increase in carbon dioxide production than in metabolic oxygen uptake as reflected by the values of respiratory exchange ratio during these conditions of vibration. Further evidence of hyperventilation is provided by the marked reduction in values of pulmonary ventilation and respiratory exchange ratio below their respective control values in the recovery period following conditions of vibration in which the pulmonary ventilation was raised. These findings agree with those of the few previous authors who have exposed human subjects to whole-body vibration at various frequencies and intensities (Duffner et al, 1962; Dixon et al, 1961; Ernsting, 1961; Hornick, 1961; Lamb & Tenney, 1966; Hood et al 1966) and who generally agree that the minute volume ventilation increases beyond that expected on the basis of oxygen consumption alone. In many cases however the evidence for true hyperventilation occurring during the period of vibration exposure has been circumstantial and ill-defined. One of the most convincing demonstrations that true hyperventilation could be induced by whole-body vibration was that given by Ernsting (1961) who measured end-expiratory and arterial carbon dioxide partial pressure in subjects exposed to constant amplitude vibration and recorded values of arterial carbon dioxide partial pressures of less than 25 mm Hg after 2 minutes of vibration at about $\pm$ 1 Gz acceleration amplitude at 9.5 Hz. In the present experiments, it has been shown that exposure of subject to vibration at frequencies 6, 8 and 10 Hz (acceleration-amplitudes, $\pm$ 0.49, $\pm$ 0.89 and $\pm$ 1.43 Gz respectively) caused a significant reduction in end tidal carbon dioxide tension with maximum reduction in these values at a forcing frequency of 10 Hz. At these frequencies the mean reduction in end-tidal carbon dioxide tensions were 3.2; 6.1 and 6.4 mm Hg for frequencies of 6, 8 and 10 Hz respectively. In three subjects moderately severe symptoms of hypocapnia (tingling of extremities, feeling of detachment) occurred during vibration at a frequency of 10 Hz. In the subjects who showed symptoms of hypocapnia, the end expiratory carbon dioxide tensions fell from values of 38 - 40 mm Hg obtained at rest, to values of 28 - 32 mm Hg obtained during the experimental vibration period. This finding provides convincing evidence that moderate to severe hyperventilation and hypocapnia can occur with exposure of the subject to whole-body, constant amplitude vibration particularly at higher intensities.

A number of suggestions have been advanced by previous workers to explain the mechanisms responsible for the occurrence of hyperventilation during exposure to low frequency structure-borne whole-body vibration, although the exact cause still remains obscure. One factor which has been considered relates to the anxiety invoked in the subject by vibration especially at the higher intensities which are liable to cause discomfort and frank pain. The results obtained in the present experiments do not however support anxiety as a causative factor in vibration induced hyperventilation. Thus, all the subjects used in the present study were highly experienced, and in the answers given in the questionnaire on completion of each vibration exposure all denied anxiety as a factor present. In addition, examination of the record of cardiac frequency obtained during the period of rest and during the transition from rest to vibration at each frequency, failed to reveal any 'anticipatory' increase in heart rate during that time, and this would also support the belief that anxiety was either minimal or absent. Although measurements of cardiac frequency obtained during vibration exposure of the subject at each frequency showed a significant increase with exposures at frequencies of 6, 8 and 10 Hz, increases in heart rate of similar magnitude were obtained by Hood, Murray, Urschell, Bowers & Clark, (1966) and by Clark, Williams, Hood & Murray, (1967) in their studies. These workers also measured mean arterial blood pressure and cardiac output during each vibration condition and believed that the rise in cardiac frequency observed in their experiments was a physiological response induced by whole-body vibration and not in any way associated with anxiety. As further support of this belief, these authors report that vibration of the anaesthetised dog (at a frequency and intensity of vibration which induced hyperventilation in man) caused marked hyperventilation in the animal under circumstances in which clearly, anxiety could be ruled out as a causative factor. It was therefore considered that anxiety was not a causative factor in the hyperventilation observed in the present series of experiments.

A number of authors have suggested that hyperventilation during whole-body vibration may arise as a result of stimulation of certain mechanoreceptors through mechanical distortion of tissues with a reflex increase in pulmonary ventilation beyond the requirements of the body. Although the existence of such a mechanism has never been proved, it would be expected that it would exert the greatest effect on ventilation in the situation where there is maximal distortion or movement of tissues and organs of the body - i.e. at a major resonance. In the review of the literature, it was shown that such a resonance in the seated human body occurs at a forcing frequency of 4 - 5 Hz and vibration at this frequency produces maximum tensile and compressional strain which might be expected to activate proprioceptors of the type suggested as responsible for the reflex hyperventilation. In the present series of experiments, however, the greatest degree of hyperventilation was obtained not at resonant but at considerably higher frequencies of vibration. This fact suggests that the hyperventilation is related more to the intensity of the vibration rather than to a pure resonance phenomenon involving stimulation of mechanoreceptors with reflex increase in ventilation. Indeed, previous attempts to demonstrate such a mechanism have failed. Thus, Lamb & Tenny, (1966) carried out a series of experiments in which they applied vibration to various parts of the body and observed the respiratory response of the subject to this vibratory stimulus. Vibrations at various frequencies and intensities applied to the lower limbs alone, caused a moderate increase in minute volume ventilation which was however proportional to the increased metabolic oxygen consumption and therefore not a true hyperventilation. In a further attempt to locate the anatomical site of possible mechanoreceptors which might be responsible for reflex hyperventilation, these workers vibrated the abdominal wall of a subject by means of an anti G suit the abdominal bladder of which was inflated by a sinusoidal air pump operating at a frequency of 6 Hz. Vibratory stimulation of the abdominal wall at intensities considerably higher than those invoked by whole-body vibration at this frequency, failed to induce hyperventilation in the experimental subject. In a further study by these authors, the application of abdominal binders to the subject during a period of vibration (known to cause hyperventilation) failed to reduce the degree of hyperventilation induced in the subject. On that experiment the effect of applying abdominal binders to the subject would be to reduce the amplitude of oscillation of the abdominal wall and to alter the resonant frequency of the thoraco-abdominal systems. In turn, this might have been expected to change the nature or magnitude of the hyperventilation induced by whole-body vibration if the causative factor was stimulation of mechanoreceptors contained in the abdominal wall viscera or diaphragm. No such change was observed, however, in the experiments described by Lamb& Tenny, and they considered that it was highly unlikely that any specific receptor site for low frequency vibration exists in the body.

Observations made during the present series of experiments suggest that hyperventilation induced in the subject during whole-body vibration may be explained on the basis of sheer discomfort experienced by the experimental subject at certain frequencies and intensities. Thus it has been shown that there is a relationship between the magnitude of the vibration stimulus and the ventilatory response. No increase in pulmonary ventilation has been found with vibration at frequencies of 2 and 4 Hz (intensities = $\pm$ 0.05 G and $\pm$ 1.43 G respectively) although at higher frequencies (6, 8 and 10 Hz) there was a marked increase in pulmonary ventilation (which was true hyperventilation), the greatest changes being found at the vibration exposure of greatest frequency and intensity (10 Hz). During exposure to vibrations at high frequency and intensity, the subject complained of acute discomfort particularly in the abdomen and chest. This discomfort was rapid in onset after the start of vibration and remained either unchanged or became more intense as the vibration exposure continued. It is generally accepted that discomfort and pain can cause an increase in the rate and depth of breathing and if of sufficient intensity can lead to hyperventilation and hypocapnia. It is believed that in the present experiments the magnitude of discomfort and pain experienced by the subjects during exposure to constant amplitude vibration at frequencies of 6, 8 and 10 Hz was sufficient to explain the hyperventilation and this is offered as the most likely factor responsible for the occurrence of the phenomenon.

In connection with the ventilatory response of subjects exposed to low frequency whole-body vibration, the effects of firm restraint by a seat harness is of considerable practical interest in aviation medicine. Ernsting (1961) suggested that the hyperventilation induced by certain conditions of whole-body vibration might be avoided or reduced if the subject could be suitably restrained in the vibrating seat, and he suggested that a formal study along these lines might yield information of considerable importance to the protection of aircrew flying in conditions of vibration at high speed and low level. In the present series of experiments a typical aircraft seat harness was used which afforded excellent restraint of the subject's torso in the vibrating seat. The results have shown however that the use of firm restraint failed to reduce the pain and discomfort associated with whole-body vibration at certain frequencies and intensities and did not protect the subject from the hyperventilation and hypocapnia induced by whole body vibration at these frequencies. Although it is believed that firm restraint of the subject in an aircraft seat will protect him against a number of the injurious effects of whole-body vibration (particularly with high intensity 'jolting' type of vibration) it is regrettably quite clear that no such protection will be offered by harness restraint against the respiratory changes induced by low frequency whole-body vibration which can occur with low-level high-speed flight.

The results of the present investigation confirm the findings of previous workers that whole-body vibration at certain frequencies and intensities induces an increase in oxygen consumption. Early research workers in Germany observed that severe whole-body vibration could increase metabolic activity in experimental subjects. In more recent measurements of oxygen consumption during whole-body vertical vibration at infrasonic frequencies the observed increases have been related to the intensity of vibration both in man (Duffner et al 1962, Ernsting 1961, Gaeuman et al, 1962) and in animals (Carter et al 1961). Ernsting recorded a significant increase only at forcing accelerations exceeding 0.5 G at a frequency of 9.5 Gz, while Gaeuman and his co-workers reported a fairly linear increase in oxygen consumption with vibrations at increasing frequencies from 6 to 15 Hz at a fixed displacement-amplitude of $\pm$ 0.132 in, the forcing acceleration ranging from $\pm$ 0.46 to $\pm$ 2.88 G. In the present experiments, the nature of vibration exposure was similar to that employed by Gaeuman and his co-workers, and the results obtained for metabolic oxygen uptake were also similar. Thus, when the subject was exposed to vibration at a constant amplitude displacement and frequencies of 2 and 4 Hz there was no significant difference between values for oxygen uptake obtained with the subject at rest and during the period of vibration exposure. During exposure to vibrations at frequencies of 6, 8 and 10 Hz there was, however, a marked increase in the oxygen consumption which was fairly linear with increasing frequency. The energy expended by the subject during exposure to vibration at the higher intensities used in this study is similar in magnitude to that expended by the pilot of a fixed wing or rotary wing aircraft during the most energetic and demanding phases of flight (e.g. instrument approaches, combat and emergency situations, etc.).

Considerable interest surrounds the nature of the mechanisms responsible for the increased metabolic oxygen uptake induced by whole-body vibration at certain frequencies and intensities. In previous studies (Ernsting, 1961; Gaeuman et al, 1962) the subjects exposed to experimental vibration sat unrestrained either on the platform of the vibrator or on a simple upright seat mounted thereon. In both these previous investigations it was suggested that the increased metabolic activity observed during the period of vibration might be due to the muscular effort required by the subject to maintain his posture in the face of violent shaking. This explanation for raised metabolic activity was also advanced by Duffner et al (1962) who reported a large increase in metabolic oxygen consumption at low frequencies rather than at resonant frequencies during exposure of these experimental subjects to constant acceleration whole-body vibration. In this latter study large vertical displacements of the vibration platform were needed to obtain the accelerative forces at the low frequencies used in their experiments. The results obtained in the present experiment suggest that muscular effort required by the subject to maintain posture is not the primary factor responsible for the increased metabolic activity during the period of whole-body vibration. Thus, it has been shown that at frequencies of 6, 8 and 10 Hz, vibration of the subject fully restrained by a harness in the vibrating seat produced increases in the values of metabolic oxygen uptake which were of the same magnitude as these obtained with the subject unrestrained in the seat and exposed to vibration at these same frequencies. In the condition in which the subject was fully restrained in the vibrating seat virtually no muscular effort was required to maintain his posture in the face of vibration. A second possible explanation for the raised metabolic activity during whole-body vibration has been considered, and this relates to the increased muscular work involved in exchanging larger quantities of gas in and out of the lungs during vibration exposure. Cherniak (1959) showed that the work of breathing accounts for only a very small percentage of the overall metabolic oxygen consumption in man, and an explanation for the increased metabolic activity during vibration must be sought elsewhere.

The results of the present investigation support the hypothesis that the increase in metabolic oxygen consumption during whole-body vibration is a result of increased muscular tension, which is unrelated to the maintenance of posture and may be either voluntary or involuntary in nature. In his early studies Cörmann (1940) observed that on exposure to whole-body vibration at certain frequencies a generalised increase in muscular tension occurred in the subject almost as soon as the vibration commenced. In the present experiments, analysis of high speed cine film taken during each vibration exposure of the experimental subject showed that a similar phenomenon occurred, with alternate tensing and relaxation of various muscular groups throughout the entire period of vibration at frequencies of 6, 8 and 10 Hz. The muscle groups involved and the durations of muscular tension and relaxation varied considerably with the nature of the forcing vibration. At the highest intensity of vibration (at a frequency of 10 Hz) it was noted that there was considerable tensing of the muscle groups in the upper and lower limbs, chest, abdomen and back in response to the vibration and that the observed muscular contraction was sustained for considerably longer periods without relaxation at the higher frequencies than at lower frequencies of vibration. It is believed that this phenomenon is responsible for the increased metabolic activity observed during whole-body vibration at frequencies of 6, 8 and 10 Hz.

The nature of the muscular response by the subject during whole-body vibration is obscure, although arguments can be made that this may be partly voluntary, as a protective mechanism, and partly involuntary due to a reflex initiated by stimulation of mechanoreceptors. In support of the fact that muscle tensing in the face of high intensity vibration is partly voluntary, it has been demonstrated in this investigation that when asked to do so the subject was able to relax his musculature voluntarily for a short period during which the muscle masses exhibited marked movement at approximately the forcing frequency of vibration. In each case, however, the subject complained that deliberate relaxation of musculature in this way intensified the pain and discomfort in abdomen, chest, head and neck particularly during exposure to vibration at high acceleration amplitudes. It is possible that voluntary tensing of muscles may be a protective mechanism which can modify the transmission of the vibration through the body to certain more vulnerable parts, or reduce the discomfort which results from movement of large groups of muscle and overlying tissues during exposure to high intensity vibration.

While part of the increase in muscular activity during whole-body vibration may be a voluntary mechanism, there is evidence from the literature which suggests that there may also be some involuntary reflex muscular tensing. The work of Guignard and Travers (1959) has shown that exposure of seated experimental subjects to vibration at frequencies of 2 - 10 Hz with a constant amplitude displacement of ± 0.33 cm elicits synchrous stretch reflexes from resting postural muscle (quadriceps) in the limbs. The amount of myotatic activity which they obtained in their experiment varied with the intensity of the applied vibration and could be reduced during whole-body vibration by restraining differential movement of the lower limbs. It is tempting to speculate that reflex muscular contraction of the involuntary type might be initiated by mechanical distortion of tissues acting possibly through muscle spindles. In this connection, it is worthy of note that Lippold, Redfearn & Vuco (1958) recorded muscle spindle discharge activity in the cat during sinusoidal muscle stretching, which was frequency dependent and had maximal facilitation at a frequency of 11 Hz. While the occurrence of reflex involuntary muscular contraction during whole-body vibration at certain frequencies must remain speculative, the possibility of such a mechanism contributing to the increased metabolic activity found in these conditions cannot be ruled out.

The practical importance in the finding of increased muscular activity during exposure to whole-body vibration lies in the effect which this may have on a pilot required to fly at high speed and low level through turbulence. In these conditions involuntary or voluntary tensing of musculature could be a significant factor contributing to fatigue.

CHAPTER 5

The modifying effects of thoraco-abdominal support on the respiratory changes induced by constant-amplitude whole-body vibration

5.1 Introduction

5.2 Methods

(a) Technique of applying support to the torso

(b) Conduct of the experiment

5.3 Results

(a) Pulmonary ventilation

(b) End-tidal carbon dioxide tension

(c) Subjective assessment of comfort/discomfort during the period of vibration

5.4 Discussion

5.5 Annex to Chapter 5

CHAPTER 5

The modifying effects of thoraco-abdominal support on the respiratory changes induced by constant-amplitude whole-body vibration

5.1 Introduction

In the previous chapter it was shown that exposure of an experimental subject to constant-amplitude whole-body vibration at frequencies between 2 Hz and 10 Hz caused an increase in pulmonary ventilation at certain frequencies. Furthermore, it was shown that under these circumstances there was a true hyper-ventilation with hypocapnia of sufficient magnitude as to cause symptoms in some subjects. It was also shown that at these frequencies of vibration in which there was hyperventilation, the experimental subject experienced considerable discomfort in the chest and to a lesser extent in the abdomen and back. It was suggested that this pain and discomfort arising during exposure of the subject to vibration at higher intensities might be responsible for the observed hyperventilation and hypocapnia. If such a hypothesis is true, then it might be expected that if steps were taken to reduce the degree of discomfort which arises during vibration at certain frequencies then this might also reduce or eliminate the hyperventilation and hypocapnia observed in the experimental subject. In the design of the experiment, described in this chapter, consideration was given to the possibility that if firm support was given to the thorax and abdomen of a subject during vibration then this might reduce the discomfort and in turn modify the respiratory changes induced by the vibration.

There is some evidence both scientific and apocryphal that abdominal support increases the human tolerance to whole-body structure-borne vibration, at least in that part of the frequency spectrum which contains the frequencies of major body resonance in man (Nickerson & Coermann, 1962; Roman, 1958). It has therefore been argued that the use of some kind of abdominal restraining device might improve the comfort and efficiency of subjects exposed to whole-body vibration of this type. Indeed, such a device in the form of an experimental anti-vibration abdominal restrainer was devised for possible use by aircrew required to fly in conditions where whole-body vibration may occur. This device, tested by Guignard (1964a) consisted of an inelastic waistband with an abdominal portion made of indistensible material and supported by three semi-rigid stays giving firm abdominal support. The whole of this experimental garment was tightened by means of two rows of adjustment laces at the back of the binder, in the manner of a Victorian lady's corset. In his study, Guignard examined the protective effect of this device using four experimental subjects exposed to vertical sinusoidal vibration at frequencies from 4.8 Hz to 16 Hz with an acceleration-amplitude of $\pm$ 0.5 Gz. The results of that study showed that exposure of the subject to vibration at certain frequencies caused a marked increase in pulmonary ventilation and respiratory rate with symptoms referable to resonance of abdominal and other viscera. Wearing the abdominal restraining device, however, had no measurable effect upon the ventilatory response of the subject or upon the dynamic response of the wearer's body to the applied vibration.

In another investigation (Guignard, 1964b) extended this study to test the anti-vibratory effects of an experimental anti G suit. This garment was similar to the anti G suit assembly worn by aircrew as a protective device during acceleration manoeuvres in aircraft and consisted of inflatable rubber bladders applied to the calves, thighs and abdomen of the wearer and supported by an outer layer of indistensible material. In Guignard's study only the abdominal portion of the anti G suit was used and this was inflated to a pressure of 1 lb/sq.in. The effect of wearing this suit with the abdominal bladder inflated was tested by exposing the experimental subject to whole-body vibration at frequencies from 4.8 Hz to 9.5 Hz with acceleration-amplitudes of $\pm$ 0.5 Gz and $\pm$ 1.0 Gz. A comparison was made of the effect of vibration at each frequency upon pulmonary ventilation with and without the subject wearing the experimental anti-G suit. In his study, Guignard noted that at certain frequencies of vibration there was a marked increase in minute volume ventilation and respiratory rate and these respiratory effects occurred whether or not the abdominal portion of the anti G suit was inflated. Despite the negative results as regards protecting the subject from the respiratory effects of whole-body vibration, a subjective assessment by questionnaire suggested that abdominal support did slightly reduce the discomfort associated with vibration at certain frequencies. In these two previous experiments, support was given only to the abdominal region of the subject and no attempt was made to provide support for the upper half of the torso. In the present series of experiments, therefore, account was taken of the findings of the experimental work described in the previous chapter, in which it was demonstrated that at certain frequencies of vibration the greatest degree of discomfort occurred in the chest. In his review, von Gierke (1971) supports the view that subcostal and substernal pain is predominant during whole-body vibration at certain frequencies and he believes that this discomfort is the prime factor limiting the ability of subjects to tolerate low frequency whole-body vibration.

It was thought therefore that the most suitable garment for use in the present series of experiments would offer support not only to the abdomen but also to the chest during experimental vibration of the subject. Such a garment exists in the form of a standard item of aircrew clothing (the combined partial pressure/anti G/air ventilated suit Mk 2) which is worn by aircrew as a protective device should they require to breathe oxygen at increased pressure in the event of emergency aircraft pressure cabin failure. This suit also provides protection against the effects of long duration acceleration (by means of anti-G bladders) and has a built-in air ventilation system. It was thought that even with the functional bladders uninflated, the suit might offer sufficient external support to the thorax and abdomen of a subject as to reduce the discomfort experienced in these areas during exposure to vibration at certain frequencies.

In the experiments described in this chapter the subject was exposed to constant-amplitude whole-body vibration at frequencies of 2, 4, 6, 8 and 10 Hz and acceleration-amplitudes of up to $\pm$ 1.43 Hz. The subject experienced each frequency of vibration on two occasions. On one occasion, he wore the combined partial pressure/anti-G/air ventilated suit while on the other occasion he did not. During each experimental run, measurements were made of pulmonary ventilation and end tidal carbon dioxide tension and the results obtained were compared for the conditions where the subject did and did not wear the experimental suit. At the end of each experimental vibration period the subject was also asked to make an assessment of the degree of comfort/discomfort which he experienced during each period of vibration. The results obtained in the study are reported in this chapter of the thesis.

5.2 Methods

(a) Technique of applying torso support

For the purpose of this experiment a standard item of air-crew equipment was used - the combined partial pressure/anti G/ air ventilated suit, Mk 2. A photograph of a subject wearing this suit is shown in figure 5.1. The suit is a one-piece garment covering torso, arms and legs, and contains inflatable bladders made from chloroprene coated nylon contained within an outer restraining layer made from terylene. Two separate sets of inflatable bladders are contained within the suit, those which when inflated provide counterpressure to torso, arms and legs (in the event of emergency loss of cabin pressure when the wearer is required to breathe oxygen at increased pressure) and those which inflate in order to protect the wearer against the effects of acceleration during high speed manoeuvres in aircraft. This latter set of bladders covers the abdomen, thighs and calves and can be inflated quite separately from the counterpressure bladders when required to do so. The entire suit can be adjusted to fit the wearer's body by means of a series of lacing cords which run down the sides of the body and leg portions. In order to allow donning of the suit, a set of sliding fasteners are incorporated; one fastener running from neck to left hip region, one on the inside of each leg and one set each at the right and left wrists. For the purposes of the present experiment the suit was fitted to each subject and the laces were adjusted to give firm support to the torso whilst the arm and leg adjustment laces were left relatively loose.

(b) Conduct of the experiment

Five experimental subjects in the age group 23 - 38 years took part in the investigation. The experiment was carried out using the mechanical vibrator and modified aircraft type ejection seat, details of which have been given previously in the Methods section of this thesis. Vibrations at frequencies of 2, 4, 6, 8 and 10 Hz were used and the total amplitude of the vibrating platform was held constant at 0.625 cm. The acceleration-amplitudes of vibration ranged from ± 0.05 Gz at a frequency of 2 Hz to ± 1.43 Gz at a frequency of 10 Hz. The acceleration-amplitude of the applied vibration was measured at the seat of the subject using a variable resistance accelerometer (range ± 10 G) mounted on the under surface of the seat pack in the vibrating seat. The output signal from this accelerometer was suitably amplified and displayed on one channel of a Devices pen recorder. In this way a continuous record of the vibration acceleration was obtained throughout the period of vibration exposure.

Figure 5. 1. Subject wearing the - combined partial pressure/ anti G/ air ventilated suit, Mk.2.

The subject was exposed to whole-body vibration in two experimental conditions. In one condition of the experiment vibration exposure was carried out with the subject seated, unrestrained by harness on the vibrating seat whilst wearing an integral protective helmet Mk 2 and a lightweight flying overall. In the other condition of the experiment, the subject wore the experimental suit (the combined partial pressure/anti G/air ventilated suit Mk 2) and a protective helmet. At each attendance, the clothing assembly worn by the subject and the frequency of the vibration was applied in a random fashion and the subjects were unaware of the object of the experiment.

Each subject sat in the vibrating seat and breathed room air through the mouthpiece of the experimental breathing circuit. Pulmonary ventilation was measured continuously by means of the recording dry gas meter and end tidal carbon dioxide concentration was measured by means of the infra red carbon dioxide meter, the sampling tube of which was inserted into the breathing circuit close to the subject's lips. Details of the measuring equipment used in this part of the investigation have been given previously in the Methods section of this thesis.

At each experimental session measurements were made of pulmonary ventilation, respiratory frequency and end tidal carbon dioxide concentration during a period of rest which lasted five minutes. Measurements were then continued throughout the period of chosen vibration which lasted five minutes, and thereafter during a five minute period of recovery following the vibration.

At the end of each experimental session, the subject was asked to complete a questionnaire relating to the degree of discomfort experienced during each period of vibration. A specimen of this questionnaire is given in Annex A of this chapter. The questionnaire called for the subject to indicate on a series of predrawn lines (each measuring 100 mm) the degree of general comfort/discomfort experienced during the period of vibration and also the degree of discomfort, if any, experienced in various anatomical sites (chest, abdomen, back) under the same experimental conditions. For each subjective assessment, a line mark value of zero indicated that the subject experienced no discomfort whatsoever during the period of vibration, whilst a line mark value of 100 mm indicated that the pain and discomfort experienced either in general or in a particular anatomical site was absolutely intolerable. Intermediate line mark values indicated the subjects assessment of the degree of comfort/discomfort between these two extremes. This type of questionnaire was designed by Gedye, Aitken & Ferres (1961) to allow quantitative measurement of subjective assessments which are amenable to standard methods of statistical analysis.

5.3 Results

(a) Pulmonary ventilation obtained with each subject during the control period of rest and during vibration at each frequency are given in Table 5.1. This table shows the values which were obtained when the subject was vibrated with and without wearing the experimental suit.

Table 5.1 Mean values of minute volume ventilation at rest and during exposure to vibration at each frequency. Five subjects vibrated with and without the experimental suit

Subject	Mean values of minute volume ventilation (Litre/BTPS) during rest and vibration at a frequency of (Hz)					
	Control (Rest)	2	4	6	8	10
			WITHOUT SUIT			
GS	8.31	8.04	7.76	11.78	14.76	15.42
ET	7.72	8.26	9.53	13.56	15.50	21.90
WW	8.29	7.35	7.84	9.42	10.33	12.48
CW	7.81	7.00	8.51	15.40	15.90	13.24
GP	7.08	7.02	7.04	10.52	16.16	16.28
			WITH SUIT			
GS	8.81	8.26	9.00	11.16	12.74	12.86
ET	7.82	7.11	8.36	9.08	13.52	15.68
WW	8.43	7.54	8.00	8.22	9.96	12.12
CW	7.08	7.16	7.34	9.40	11.44	12.42
GP	7.51	6.38	7.22	11.26	15.48	14.31

It may be seen by reference to Table 5.1 that in both experimental conditions (i.e. subject wearing and not wearing the suit) there was an increase in pulmonary ventilation during the period of exposure to vibration at frequencies of 6, 8 and 10 Hz. The values of pulmonary ventilation obtained at these frequencies were significantly greater than those obtained during the control period of rest ($P = 0.001$). During exposure to vibration at frequencies of 2 and 4 Hz, there was no significant increase in pulmonary ventilation for either condition of the experiment. Analysis has shown that when the subject wore the experimental suit during vibration the mean increases in pulmonary ventilation over those obtained at rest were 23.8%, 59.3% and 69.9% for frequencies of 6, 8 and 10 Hz respectively. When, however, the subject was exposed to vibration at these frequencies (6, 8 and 10 Hz) without wearing the suit, the increases in pulmonary ventilation over resting control values were 54.8%, 85.3% and 102.3% respectively. The ventilatory responses with exposure to vibration at frequencies of 6, 8 and 10 Hz were significantly lower ($P = 0.001$) when the subject wore the suit than when he did not.

The increase in pulmonary ventilation obtained during exposure of the subject to vibration occurred mainly as a result of an increase in respiratory frequency with only a small increase in tidal volume. Mean values of respiratory frequency obtained for each subject at rest and during exposure to vibration at each forcing frequency are given in Table 5.2 for two conditions of the experiment (subject vibrated with and without the experimental suit). It may be seen by reference to this table that in both conditions of the experiment whole-body vibration at frequencies of 6, 8 and 10 Hz caused an increase in values of respiratory frequency over those obtained with the subject at rest. ($P = 0.001$).

The values of respiratory frequency which were obtained during the condition of the experiment in which the subject wore the suit during vibration were 8.5%, 24.0%, and 38.7% greater than resting control values for frequencies of 6, 8 and 10 Hz. The values obtained with exposure to vibration, when the subject did not wear the suit, were 25.8%, 50.3% and 68.9% greater than control values for frequencies of 6, 8 and 10 Hz. The values of respiratory frequency obtained during the period of vibration were significantly lower in the condition in which the subject wore the suit than when he did not. ($P = 0.001$)

(b) End tidal carbon dioxide tension

Values of end tidal carbon dioxide tension were calculated for each breath from the record obtained of end tidal carbon dioxide concentration with the subject at rest and during each experimental vibration exposure. The mean values of end tidal carbon dioxide tension obtained with the five experimental subjects at rest, during vibration at various frequencies and during subsequent recovery from vibration are shown in Table 5.3. This table shows values obtained with the subject exposed to vibration at each forcing frequency in the conditions of the experiment in which he wore the experimental suit and in these conditions in which he did not.

Table 5.2 Mean values of respiratory frequency obtained with subject at rest and during exposure to vibration at various frequencies in two experimental conditions (with and without the experimental suit)

Subject	Mean values of respiratory frequency (breaths/min.) obtained during rest and vibration at the following frequencies (Hz)					
	Rest	2	4	6	8	10
			WITHOUT SUIT			
GS	12.1	12.0	11.9	14.2	17.1	18.7
ET	12.3	12.4	12.6	15.1	18.2	19.3
WW	12.3	12.3	12.2	16.1	18.2	21.4
CW	11.9	12.2	11.4	15.8	19.2	22.5
GP	12.2	12.1	12.5	15.3	18.7	20.8
			WITH SUIT			
GS	12.3	11.9	12.1	13.3	15.1	16.2
ET	11.9	11.4	12.0	12.6	14.8	17.1
WW	12.6	11.6	12.4	12.9	15.1	16.8
CW	13.2	12.8	13.1	14.2	15.8	18.1
GP	12.0	13.0	12.8	14.3	16.1	17.8

Table 5.3 Mean values of end-tidal carbon dioxide tension for five subjects at rest and during exposure to vibration at various frequencies (with and without the experimental suit)

Frequency of vibration (Hz)	Mean value of end tidal carbon dioxide tension (mm Hg)					
	WITHOUT SUIT			WITH SUIT		
	Rest	Vibration	Recovery	Rest	Vibration	Recovery
2	39.5	39.7	39.5	39.2	39.8	39.4
4	39.4	40.0	39.3	38.7	37.9	38.2
6	40.0	35.2*	37.6	39.5	39.7	39.0
8	39.7	33.0*	38.2	39.7	35.4*	38.6
10	39.6	32.1*	36.3	38.8	33.1*	38.0

* values during vibration significantly different from values obtained at rest ($P = 0.001$)

It may be seen by reference to Table 5.3 that in the experimental condition where the subject did not wear the experimental suit, exposure to vibration at certain frequencies caused a marked fall in end tidal carbon dioxide tension from values obtained during the control period of rest. Thus, with vibration at frequencies of 6, 8 and 10 Hz the end tidal carbon dioxide tension fell during the period of vibration by values of 4.8, 6.7 and 7.5 mm Hg respectively. These values of end tidal carbon dioxide tension obtained during the period of vibration exposure were significantly greater than those obtained at rest ($P = 0.001$). During exposure to vibration at a frequency of 10 Hz, one subject (not wearing the experimental suit) complained of symptoms which were highly suggestive of hypocapnia (tingling of fingers and toes). In this subject the end tidal carbon dioxide tension fell from a mean value of 39.4 mm Hg obtained during the resting period, to 29.7 mm Hg during the period of vibration.

It may be seen by reference to Table 5.3 that the changes in end tidal carbon dioxide tension obtained with the subject wearing the experimental suit during the period of vibration were in sharp contrast to the condition where the subject did not wear the suit. Thus, with exposure of the subject wearing the experimental suit to vibration at a frequency of 6 Hz there was no measurable change in values of end tidal carbon dioxide tension over values obtained at rest. With vibration at a frequency of 8 Hz, the mean value of end tidal carbon dioxide tension fell by 4.3 mm Hg (compared with 6.7 mm Hg at the same frequency with the subject <u>not</u> wearing the suit), and with vibration at a frequency of 10 Hz the mean value of end tidal carbon dioxide tension fell by 5.7 mm Hg (this compared with a fall in the mean value of end tidal carbon dioxide tension of 7.5 mm Hg obtained during vibration at 10 Hz with the subject not wearing the suit). In the condition of the experiment in which the subject wore the experimental suit, there were no complaints of symptoms which could be referred to hypocapnia.

The mean changes in end tidal carbon dioxide tension obtained in the two experimental conditions are shown graphically in figure 5.2. It is clear from Table 5.3 and figure 5.2 that wearing of the experimental suit during the period of vibration prevented hyperventilation and hypocapnia in the subject exposed to vibration at a frequency of 6 Hz and markedly reduced the hypocapnia which occurred with exposure to vibration at frequencies of 8 and 10 Hz.

(c) <u>Subjective assessment of comfort/discomfort during the period of vibration</u>

An analysis was made of the replies to the questionnaire relating to comfort/discomfort experienced by each subject during each vibration run. Mean values for general subjective discomfort and for discomfort experienced in various anatomical sites during exposure to vibration are presented in Table 5.4 for two conditions of the experiment (i.e. subject wearing and not wearing the experimental suit). It may be seen from this table that the subjective assessments for general comfort/discomfort obtained during the period of vibration at frequencies of 6, 8 and 10 Hz indicate that at these frequencies of vibration the subjects were more comfortable when they were wearing the experimental suit than when they were not. In addition it may be seen from Table 5.4 that vibration at frequencies of 6, 8 and 10 Hz caused considerably less discomfort in chest, abdomen and back of the

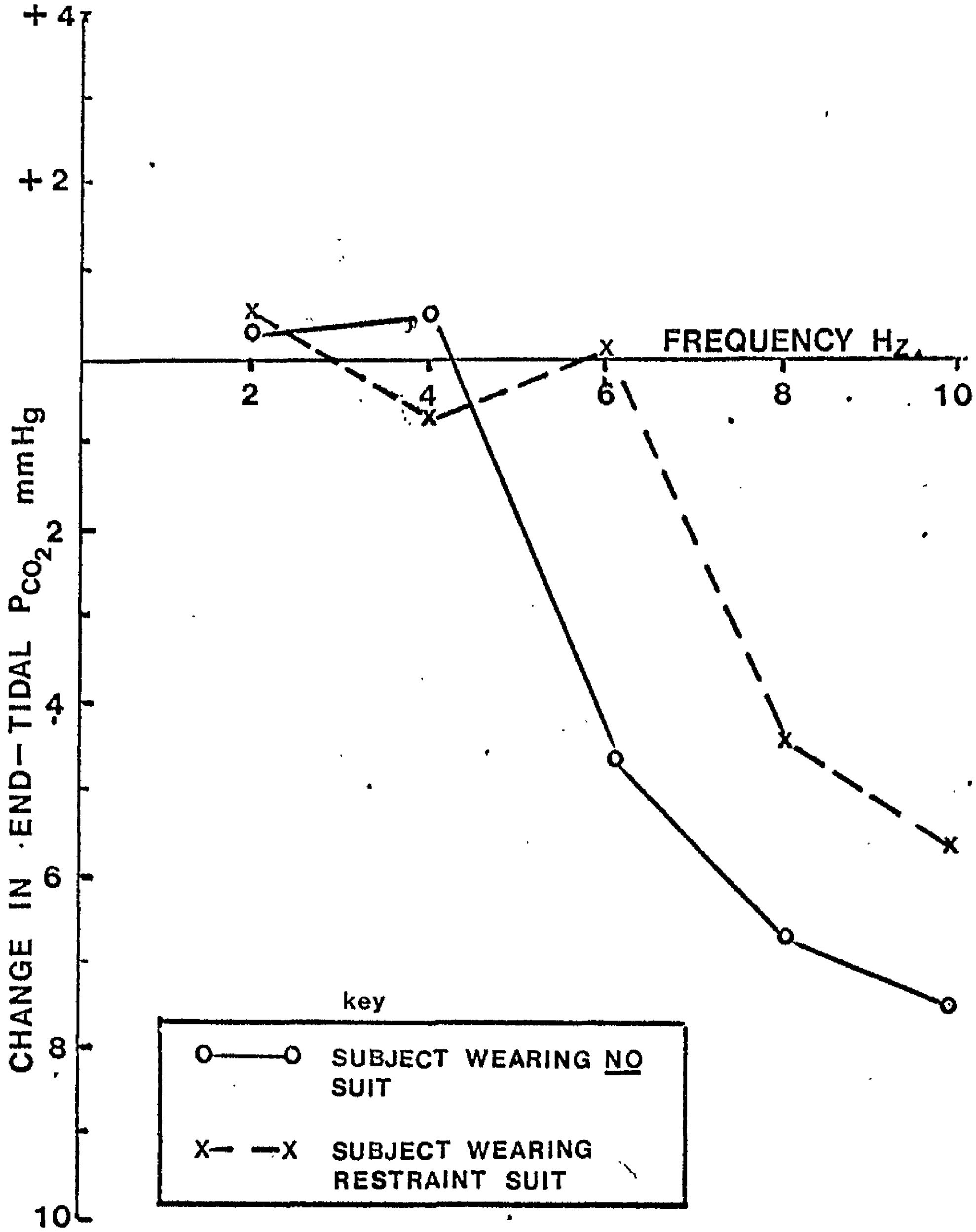


Figure 5. 2. Change in end-tidal carbon dioxide tension during vibration at various frequencies. Subject wearing and not wearing the suit.

Table 5.4 Mean values for line marking subjective assessment of comfort/discomfort during whole-body vibration at various frequencies. Mean of five subjects wearing and not wearing experimental suit

Frequency of vibration (Hz)	Mean value of line marking assessment of comfort. Measured from the left of the line (mm)*	
	Wearing suit	Not wearing suit
	GENERAL COMFORT	
2	0.2	0.3
4	4.5	4.7
6	11.3	19.5
8	31.3	66.1
10	46.9	82.5
	ABDOMINAL COMFORT	
2	0.4	0.3
4	0.1	2.6
6	0.5	9.1
8	1.7	25.0
10	4.5	47.6
	CHEST COMFORT	
2	0.3	0.2
4	0.2	2.9
6	3.9	4.8
8	25.5	72.0
10	58.6	75.4
	BACK COMFORT	
2	0.0	0.2
4	1.0	4.3
6	0.0	0.4
8	20.4	20.5
10	38.5	40.6

subject when he was wearing the suit than when he was not. The data for subjective assessment of comfort/discomfort as indicated on the line marking questionnaire was analysed using the 'Wilcoxon-matched-pairs-signed-ranks' test. This analysis has shown that the differences in both general comfort assessment and assessment of comfort in abdomen and chest of the subject in the two conditions of the experiment (vibrated with and without wearing the suit) are significant with vibration at frequencies of 8 and 10 Hz ($P = 0.01$) and at a frequency of 6 Hz ($P = 0.05$). There was, however, no significant difference in the values of indicated subjective discomfort in the back for the two conditions of the experiment.

The results for the subjective assessments of general comfort and for comfort/discomfort experienced in the two main anatomical sites (abdomen and chest) during exposure of the subject to vibration at various frequencies are presented graphically in figure 5.3.

5.4 Discussion

These experiments have confirmed the findings of the previous study (described in chapter 4) that constant amplitude whole-body vibration at certain frequencies causes an increase in pulmonary ventilation in the experimental subject, which is brought about by a moderate increase in tidal volume and a marked increase in respiratory frequency. Furthermore it has confirmed the fact that the increase in minute volume ventilation induced by vibration at certain frequencies is a true hyperventilation with hypocapnia. As in the previous study it has been shown that the degree of hyperventilation and hypocapnia increases almost linearly with increasing intensity of vibration exposure with maximum values being obtained at the highest intensity of vibration used in this study (frequency = 10 Hz, acceleration-amplitude = $\pm$ 1.43 Gz).

The important finding in this part of the overall investigation is that the increase in pulmonary ventilation brought about by exposure of the experimental subject to whole-body vibration at frequencies of 6, 8 and 10 Hz was greatly reduced when an experimental garment giving firm support to the abdomen and chest was worn by the subject during the period of vibration exposure. Furthermore, it has been demonstrated that when this garment was worn by the experimental subject, the hypocapnia induced by vibration at these frequencies was either eliminated or greatly reduced. The findings of this experiment also show that when the experimental suit was worn by the subject during the period of vibration it offered a considerable degree of protection against the discomfort and pain associated with vibration at frequencies of 6, 8 and 10 Hz. This finding supports the hypothesis advanced in the previous chapter of the thesis that pain and discomfort experienced by the subject during constant-amplitude whole-body vibration at certain frequencies may be of sufficient magnitude as to induce the ventilatory changes found with these conditions of vibration.

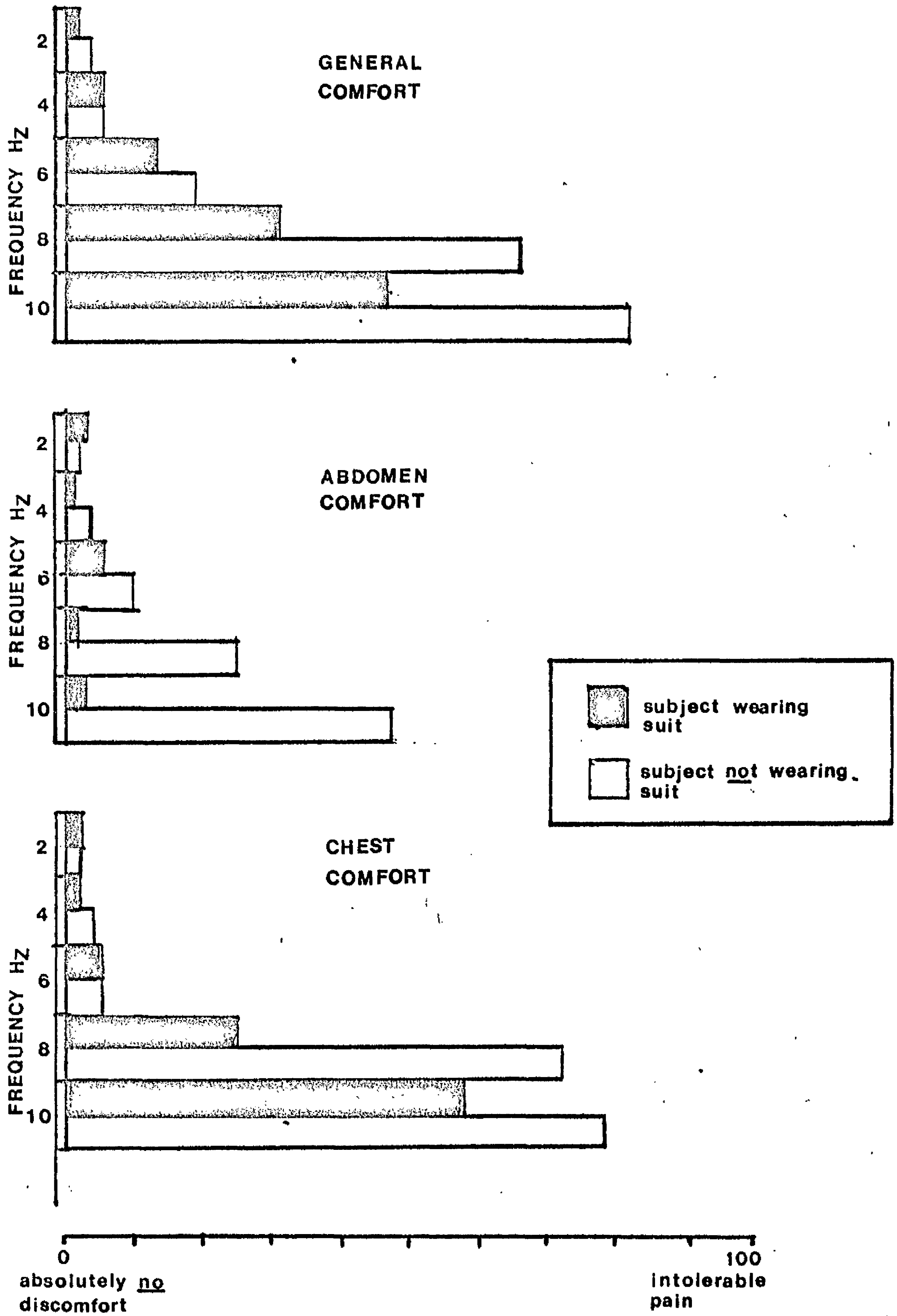


Figure 5. 3. Subjective ratings for comfort/discomfort during vibration with and without the experimental suit.

This belief is further reinforced by the fact that protection from the respiratory changes associated with constant-amplitude low frequency vibration was achieved by providing the subject with a suit which gave firm support not only to the abdomen but also to the chest. It may be recalled that in the previous series of experiments in which subjects were exposed to constant-amplitude vibration at frequencies of 2 - 10 Hz the greatest degree of discomfort experienced by the subject during certain conditions of vibration occurred in the chest region and only to a lesser extent in the abdominal area. It is likely that failure to support the chest during the period of vibration may explain the negative findings of Guignard (1964 a and b) in his assessment of various garments designed to protect the subject against the effects of vibration.

There are two possible explanations for the mechanism whereby the application of firm thoraco-abdominal support reduces or eliminates the respiratory changes induced by constant amplitude whole-body vibration at certain frequencies. One possibility is that the experimental suit caused a stiffening of the torso in the subject during the period of vibration and thereby modified the distribution of the input vibration stimulus through the body. Nickerson & Coermann (1962) showed that stiffening of the trunk during exposure to whole-body vibration can alter the transmissibility of the vibration in the body and can protect certain parts from the differential movement induced by the vibratory stimulus. It seems more likely, however, that the application of external support to the abdominal wall reduced the degree of painful oscillatory movement of viscera and that similar support to the thorax reduced the movement of pectoral muscle masses during exposure of the subject to whole-body vibration at certain frequencies and intensities.

Whatever the protective mechanism involved might be, the practical importance of the findings of this experiment lies in the fact that it offers a possible solution to improving the comfort, safety and wellbeing of the aviator exposed to conditions of vibration in-flight. At the present time, very little is known about the subjective discomfort associated with random vibration in aircraft and work is currently being undertaken to assess this. The results of the present study show that if future advances in the operation of military aircraft expose the pilot to conditions of vibration which give rise to severe discomfort and associated respiratory changes, then steps can be taken to reduce or eliminate these effects by providing him with thoraco-abdominal support. Furthermore, it has been shown that even moderate support of the type offered by a current item of aircrew clothing will provide adequate protection against the adverse effects of certain types of structure borne whole-body vibration.

5.5 Annex to Chapter 5

SPECIMEN OF QUESTIONNAIRE

Experiment A 0164 Date ....

Equipment: .... Run No. .... Subject ....

Please consider carefully the vibration exposure which you have just experienced and indicate your assessment of comfort/discomfort in the following manner:

> Place a single vertical stroke through the appropriate pre-drawn line according to your own personal rating of comfort during the period of vibration. If you experienced little discomfort during vibration mark the line to left of centre; if you found it very uncomfortable mark the line to the right of centre. The further away from centre (either way) you mark the line, the stronger your feelings about this condition of vibration. Please use the ends of the line only if you think the wording appropriate.

GENERAL COMFORT

Absolutely no discomfort ________________________________ Intolerable discomfort

COMFORT IN CHEST

Absolutely no discomfort	Intolerable discomfort

COMFORT IN ABDOMEN

Absolutely no discomfort	Intolerable discomfort

COMFORT IN BACK

Absolutely no discomfort	Intolerable discomfort

CHAPTER 6

The respiratory effects of whole-body vibration at a constant acceleration-amplitude

6.1 Introduction

6.2 Methods

6.3 Results

- (a) Pulmonary ventilation
- (b) End expiratory carbon dioxide tension
- (c) Metabolic oxygen uptake
- (d) Carbon dioxide output
- (e) Respiratory exchange ratio
- (f) Symptoms arising during whole-body vibration

6.4 Discussion

CHAPTER 6

The respiratory effects of whole-body vibration at a constant acceleration-amplitude

6.1 Introduction

In an earlier chapter (chapter 4) the respiratory changes induced by whole-body vibration were studied using conditions of vibration in which the displacement amplitude was held constant and the intensity of the vibration increased with an increase in forcing frequency (constant amplitude vibration). An alternative approach to studies of the human responses to vibration can be made using conditions of vibration in which the total displacement of the vibration platform is adjusted in such a way as to maintain a constant acceleration-amplitude over the range of frequencies studied. By using both types of experimental vibration, physiological responses can be studied over a wide range of frequencies and acceleration-amplitudes.

There have been very few investigations, however, of the respiratory changes induced by constant acceleration vibration, although in their experiments Duffner et al (1962) found an increase in metabolic oxygen consumption and pulmonary ventilation at the lower frequencies of vibration studied (range 2 - 7 Hz). These workers demonstrated that hyperventilation occurred in their subjects during exposure to vibration at frequencies of

4 - 5 Hz and they believed that this might have been brought about by stimulation of certain deformation receptors situated in various parts of the body. Ernsting (1961) also used constant acceleration vibration (acceleration-amplitude = $\pm$ 0.25G) and noted that there was an increase in pulmonary ventilation in his experimental subjects which was greatest at the lowest frequency used (1.7 Hz). Since this frequency of vibration is below that of any known mechanical resonance of the respiratory system and was not accompanied by any discomfort on the part of the subject, this respiratory effect was tentatively attributed to labyrinthine stimulation. This explanation was also advanced by Dixon et al (1961) who produced marked hypocapnia in their subjects exposed to vibration at a constant acceleration and at frequencies between 0.5 and 0.8 Hz.

In reviewing the literature, it is of interest to note that in previous reports the respiratory changes induced in the experimental subject by vibration at constant acceleration were observed at the lower end of the range of frequencies studied. This contrasts with the situation during exposure of the subject to constant amplitude vibration where it has been shown that the respiratory changes occur at the higher frequencies in the range studied. This suggests that there may be a difference in the causative mechanisms involved in the respiratory changes observed in the two experimental conditions.

In the present investigation, therefore, experiments were designed to study the respiratory effects of whole-body vibration held at a constant acceleration-amplitude over a range of frequencies; to define the magnitude of these changes and to attempt to elucidate the physiological mechanisms involved in their production. In this series of experiments the frequencies of vibration studied were 2, 4, 6, 8 and 10 Hz and the acceleration-amplitude was held constant for each frequency at $\pm$ 0.4 Gz. The results obtained for this series of experiments are reported in this chapter of the thesis.

6.2 Methods

Eight experimental subjects in the age group 23 - 42 years took part in this series of experiments. Seven of the subjects had participated in the previous experiments reported in chapter 4 of this thesis (the constant-amplitude vibration series). One subject who took part on the previous occasion was unable to participate (subject AC) and he was replaced by another subject (ET) who had similar anthropometric characteristics. The details of height, weight and body surface area of the eight experimental subjects used in this study are given in Table 6.1.

Table 6.1 Details of height, weight and body surface area of the eight experimental subjects used in the study

Subject	Height (cm)	Weight (kg)	Body surface area (m2)*
AM	176.5	72.5	1.88
GS	173.9	74.1	1.87
ET	175.3	70.1	1.80
WW	175.3	72.9	1.88
CW	174.6	66.4	1.77
GP	171.5	67.2	1.79
ED	190.5	74.1	2.02
PF	193.0	80.5	2.18

* Body surface area computed from the nomogram of DuBois (1936)

The experiments were carried out using the mechanical vibrator upon which was mounted a modified aircraft type ejection seat. Details of the vibration equipment and the seat have been given previously in the Methods chapter of this thesis (chapter 3). Vibrations at frequencies of 2, 4, 6, 8 and 10 Hz were used in this study and for each forcing frequency of vibration, the total displacement of the vibrating platform was adjusted to give a constant acceleration-amplitude of ± 0.4 Gz. The acceleration-amplitude of vibration was measured at the seat of the subject throughout each experimental vibration session using a variable resistance accelerometer (range ± 10 G), appropriate amplifier and pen recorder.

Each experimental subject attended on ten separate occasions. On half the number of attendances the experiments were conducted with the subject sitting in the vibration seat fully restrained by means of an aircraft type harness system (described in chapter 3) and on the other half of the attendances the subject was completely unrestrained in the seat. Exposure of the subject to each frequency of vibration (2 - 10 Hz) and the condition of restraint were carried out in a random fashion, and the subjects were unaware of the object of the experiment.

Each subject wore a lightweight Royal Air Force flying coverall and a standard protective flying helmet (RAF Mk 2) each of which was fitted using aircrew fitting procedures, and he sat either restrained or unrestrained by harness in the vibration seat with his feet resting on the footrest. The breathing circuit used by the subject was identical to that used in the constant amplitude vibration studies and this equipment has been described in detail in chapter 3 of this thesis. The subject breathed room air from this breathing circuit using a mouthpiece while the nostrils were occluded by a nose clip. Expired gas was conducted from the expiratory port of the valvebox in the breathing circuit first to the recording dry gas meter and then into gas collection equipment (these have been described in detail in a previous chapter). End tidal carbon dioxide concentration was measured using an infra-red carbon dioxide meter, the sampling line of which was inserted into the valvebox close to the lips of the subject. The output from this meter was suitably amplified and displayed on a single channel of an Esterline Angus pen recorder.

At each experimental session, the subject rested for a period of five minutes during which no recordings were taken. During a further period at rest, measurements were made of pulmonary ventilation and end tidal carbon dioxide concentration and expired gas was collected in a Douglas bag over the last three minutes of the rest period. The subject was then exposed to the chosen condition of vibration for a total period of ten minutes during which measurements were made continuously of pulmonary ventilation and end tidal carbon dioxide concentration. Collections of expired gas were made on two occasions during the vibration period. The first collection was taken over a period of three minutes (between minute 2 and minute 5 of vibration) and the second collection was made between minute 7 and minute 10 of the vibration period. For convenience, these collections will be referred to, hereafter, as samples after five and ten minutes of vibration. Vibration exposure was followed by a recovery period lasting five minutes during which measurements of pulmonary ventilation and end tidal carbon dioxide concentration were continued and a final collection of expired gas was taken in the last three minutes of the recovery phase. Values of minute volume ventilation and respiratory frequency were calculated from the recordings obtained for each minute of the control, vibration exposure and recovery phases of the experiment. Values of end tidal carbon dioxide concentration were calculated from the maximum deflection of the trace recorded with each breath from the output signal of the carbon dioxide meter. Values of metabolic oxygen uptake, carbon dioxide output and respiratory exchange ratio were calculated from pulmonary ventilation and analysis of the expired gas for oxygen and carbon dioxide concentrations. The techniques of measurement and the calculations involved in this procedure have been described in detail in a previous chapter.

6.3 Results

(a) Pulmonary ventilation

Mean values of minute volume ventilation for the eight subjects taking part in the experiment are shown in Table 6.2 for the period of rest, after five minutes and ten minutes exposure to vibration at each frequency and during subsequent recovery. Values obtained with the subject seated fully restrained in the vibration seat are shown together with those obtained when the subject was unrestrained in the seat. The mean values of pulmonary ventilation are shown graphically in figure 6.1 for each minute of rest, exposure to vibration and subsequent recovery.

Table 6.2 Mean values of pulmonary ventilation at rest, during vibration exposure and recovery. Eight subjects restrained and unrestrained in the vibration seat

Frequency of vibration (Hz)	Pulmonary ventilation (L/min BTPS) during:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	9.24	11.15	9.86	8.37
4	9.32	10.92	9.98	7.55
6	9.90	12.58	10.58	8.42
8	9.60	10.82	10.52	8.56
10	9.30	9.75	9.48	8.02
		UNRESTRAINED		
2	9.64	11.43	10.20	8.60
4	9.41	11.58	11.43	8.14
6	8.98	11.69	10.68	7.75
8	9.27	10.48	9.56	8.30
10	9.80	10.61	10.35	9.13

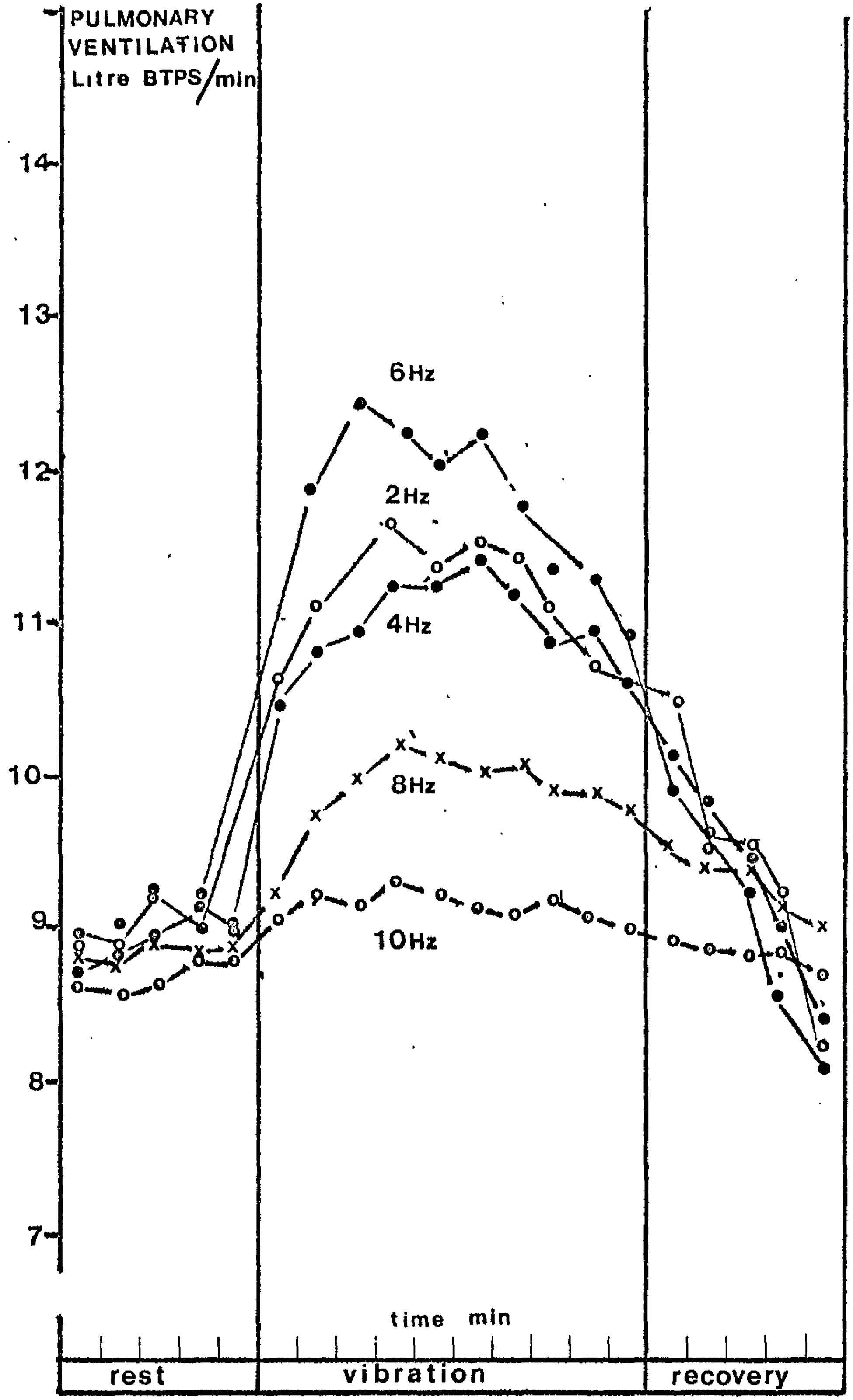


Figure 6. 1 Pulmonary ventilation during exposure to vibration at a constant acceleration-amplitude.

An Analysis of Variance carried out on the data on pulmonary ventilation obtained in the present experiment has shown that there was no significant difference in values obtained with the subject vibrated either unrestrained or restrained by harness in the vibrating seat. It may be seen by reference to Table 6.2 and figure 6.1 that after five minutes exposure of the subject to vibration at a constant acceleration-amplitude there was an increase in pulmonary ventilation only at frequencies of 2, 4 and 6 Hz. In these conditions of vibration in which an increase in pulmonary ventilation was obtained, this occurred within half to one minute after the start of vibration, reached a maximum value after five minutes vibration and thereafter declined in magnitude towards the end of the ten minute period of vibration. The values of pulmonary ventilation obtained during the recovery period following vibration exposure at each frequency were significantly reduced below values obtained during the resting control period ($P = 0.001$).

Analysis has also shown that the increases in pulmonary ventilation observed after 5 min and 10 min of vibration exposure at frequencies of 2, 4 and 6 Hz were significantly greater than those obtained with the subject at rest ($P = 0.001$). The greatest increase in pulmonary ventilation (28.5% increase over resting values) occurred during exposure of the subject to whole-body vibration at a frequency of 6 Hz. With exposure of the subject to vibration at frequencies of 2 and 4 Hz the increase in values of pulmonary ventilation over those obtained with the subject at rest were 19.6% and 19.9% respectively. There was, however, no significant change in pulmonary ventilation with exposure of the subject to vibration at frequencies of 8 and 10 Hz.

Examination of the data has revealed that at these frequencies of vibration in which a change occurred in pulmonary ventilation, that change was brought about by an increase in tidal volume, the respiratory frequency remaining virtually unchanged throughout the vibration and recovery periods. The mean values of respiratory frequency obtained with the subject at rest, during vibration exposure at each frequency and during subsequent recovery from vibration are shown for the eight experimental subjects in Table 6.3.

(b) End Tidal carbon dioxide tension

The mean changes induced in end tidal carbon dioxide tension by whole-body vibration at a constant acceleration and various frequencies are shown in Table 6.4 and are presented graphically in figure 6.2. In Table 6.4 the value for carbon dioxide tension obtained with the subject at rest is shown together with the carbon dioxide tension which existed after 5 minutes and 10 minutes exposure to vibration and during the subsequent recovery phase. It may be seen that the reduction in end tidal carbon dioxide tension was greatest at the lower frequencies of vibration (2 Hz and 4 Hz) used in this study. The greatest change in values of

Table 6.3 Mean values of respiratory frequency with the subject at rest, during exposure to vibration at frequencies between 2 and 10 Hz and during subsequent recovery from vibration. Eight subjects restrained and unrestrained in the vibrating seat

Frequency of vibration (Hz)	Respiratory frequency (breaths/min) during :			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	11.3	11.8	11.6	10.9
4	12.0	11.6	10.9	11.2
6	12.7	11.8	12.1	12.2
8	13.6	13.8	13.0	12.9
10	11.6	11.6	12.2	11.3
		UNRESTRAINED		
2	12.7	11.9	12.1	12.6
4	12.2	11.6	12.0	12.5
6	10.2	11.1	10.8	10.7
8	11.8	12.5	13.0	12.6
10	11.6	12.2	12.0	12.4

end tidal carbon dioxide tension occurred within the first five minutes of the vibration period after which they returned towards control values in the last minutes of the period of vibration. Analysis of the results have shown that there was no significant difference between values of end tidal carbon dioxide tensions obtained with the subject restrained and unrestrained in the vibration seat.

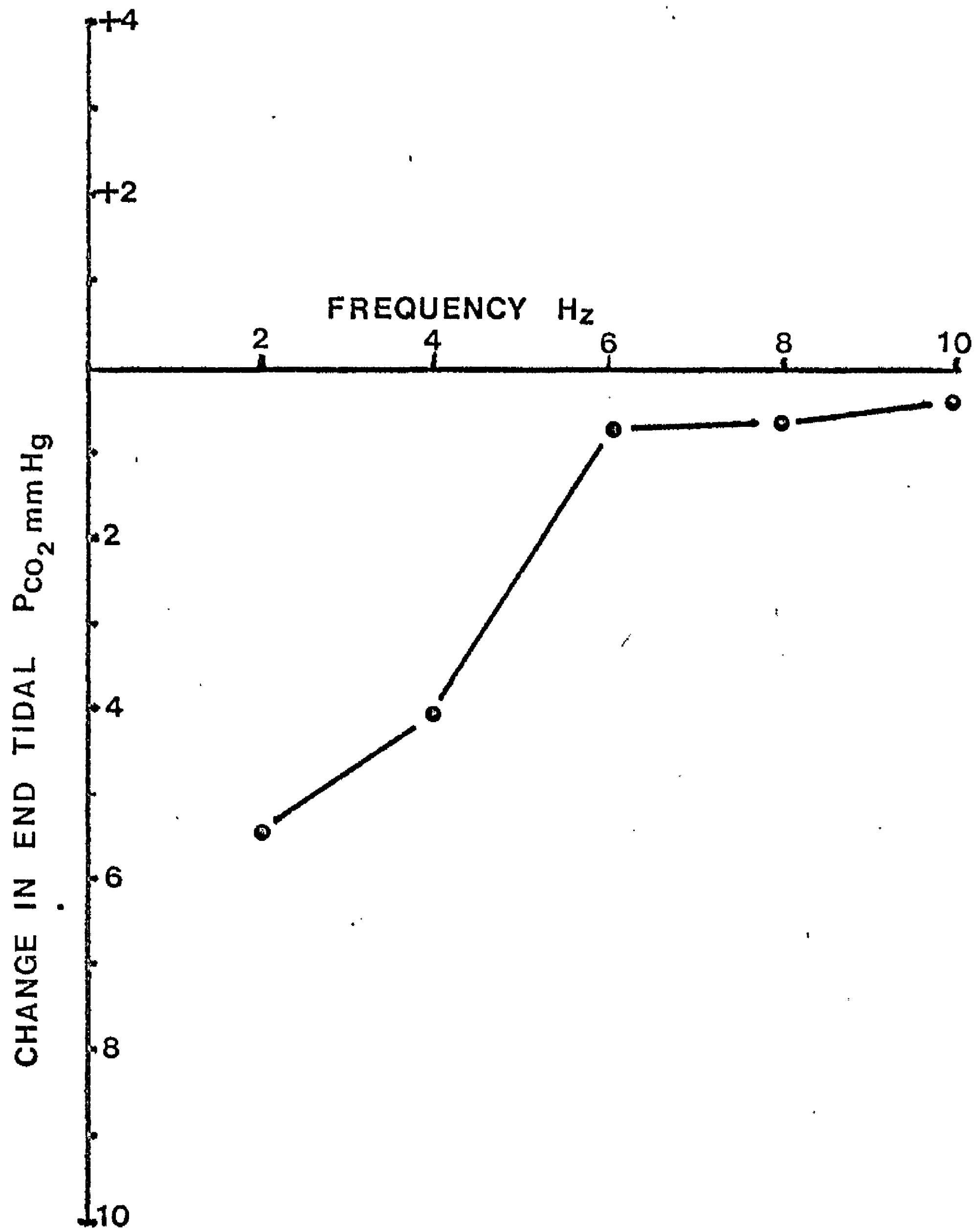
Table 6.4 The effect of whole-body vibration at a constant acceleration-amplitude upon end tidal carbon dioxide tension. (Pooled values for eight subjects restrained and unrestrained in the vibration seat.)

Frequency of vibration (Hz)	Mean value of end tidal carbon dioxide tension (mm Hg) during :			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
2	39.6	34.3	38.2	39.3
4	39.5	35.4	38.0	38.7
6	40.2	39.4	38.7	39.1
8	39.2	38.4	38.5	40.2
10	39.9	39.2	38.7	39.5

(c) Metabolic oxygen consumption

The mean values of oxygen consumption which were obtained during this series of experiments are presented in Table 6.5 for eight subjects in a restrained and unrestrained condition in the seat and exposed to frequencies of 2, 4, 6, 8 and 10 Hz at a constant acceleration-amplitude ($\pm$ 0.4 Gz).

It may be seen by reference to Table 6.5 that during exposure to vibration at certain frequencies (both with the subject restrained and unrestrained in the vibrating seat) there was a moderate increase in metabolic oxygen consumption which reached a maximum value after five minutes of exposure to vibration and thereafter declined towards the end of the period of vibration. Analysis



<u>Figure 6. 2</u> Change in end tidal carbon dioxide tension, during exposure to vibration at a constant acceleration-amplitude.

Table 6.5 Effect of whole-body vibration (constant acceleration) upon metabolic oxygen consumption. Eight experimental subjects exposed to vibration at various frequencies while restrained and unrestrained in the vibration seat

Frequency of vibration (Hz)	Mean value of metabolic oxygen consumption (L/min STPD) in the following conditions:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	0.304	0.335	0.311	0.298
4	0.300	0.340	0.326	0.278
6	0.322	0.398	0.351	0.297
8	0.313	0.312	0.318	0.293
10	0.307	0.313	0.297	0.283
		UNRESTRAINED		
2	0.321	0.351	0.350	0.313
4	0.313	0.370	0.356	0.282
6	0.287	0.356	0.324	0.261
8	0.302	0.314	0.297	0.280
10	0.306	0.311	0.319	0.308

of the data has shown that with exposure to vibration at frequencies of 2 Hz and 4 Hz the mean values of oxygen consumption were significantly greater in the condition in which the subject was unrestrained in the vibrating seat than when he was fully restrained ($P = 0.01$). On the other hand, there were no significant differences for conditions of restraint during exposure of the subject to vibration at frequencies of 6, 8 and 10 Hz. This observation is of considerable interest in explaining the mechanism involved in the increase of metabolic activity during exposure of the subject to low frequency vibration at a constant acceleration-amplitude. The results for metabolic oxygen consumption obtained in this experiment are shown graphically in figure 6.3.

Analysis has also shown that the increase in metabolic oxygen consumption observed after 5 min and 10 min exposure to vibration at a frequency of 6 Hz was significantly greater than that obtained with the subject at rest prior to vibration ($P = 0.001$). The mean value for metabolic oxygen consumption obtained during vibration at this frequency was 26.7% greater than that obtained with the subject at rest. It is noteworthy that the increase in metabolic oxygen consumption obtained during vibration at a frequency of 6 Hz almost exactly balanced the increase in pulmonary ventilation obtained during exposure of the subject to vibration at the same frequency.

Analysis has shown that with exposure of the subject to vibration at frequencies of 2 and 4 Hz there was a moderate but significant increase in values of metabolic oxygen consumption over those obtained with him at rest ($P = 0.001$). The mean values of metabolic oxygen consumption obtained in these conditions of vibration were respectively 19.6% and 19.9% greater than those obtained during the period of rest. It is of particular importance

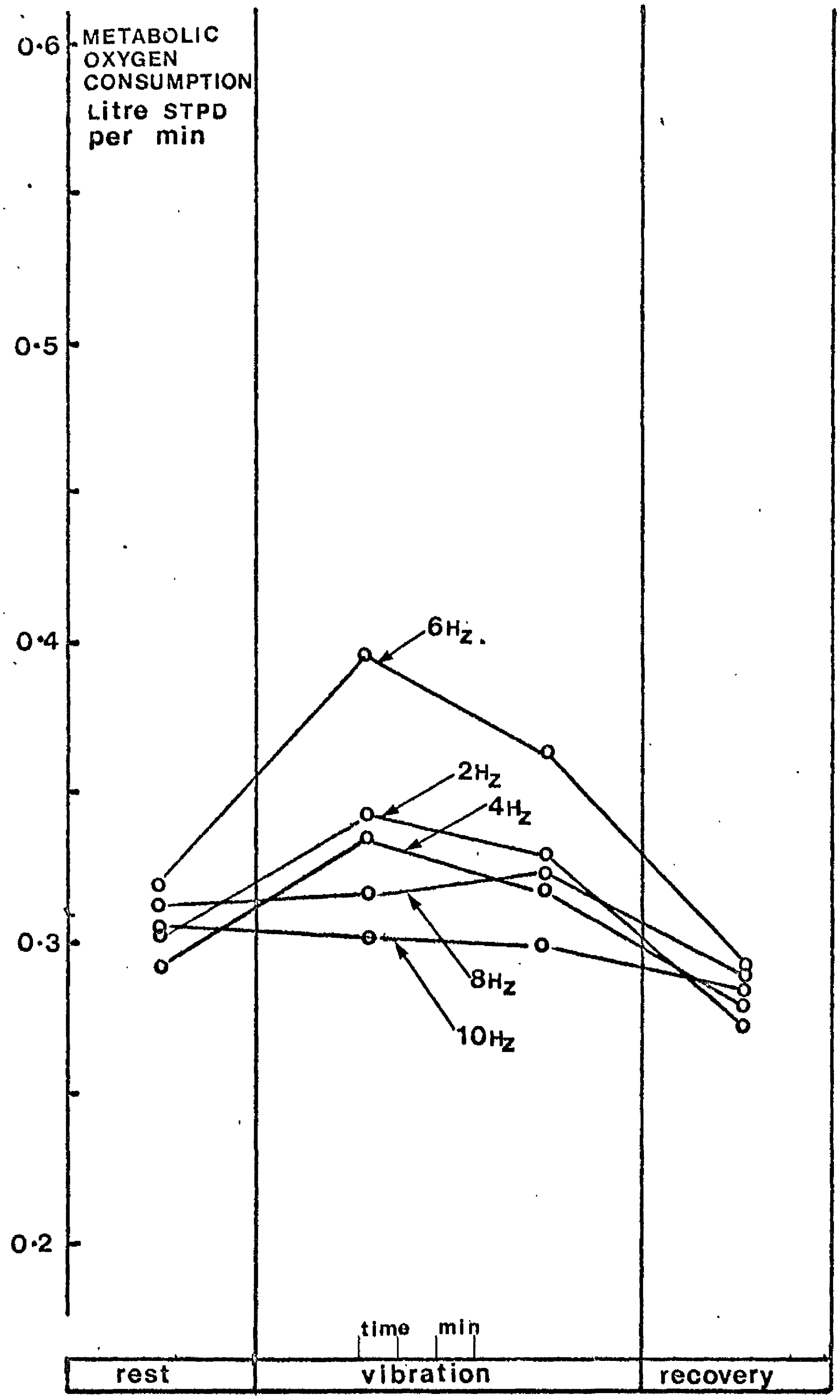


Figure 6. 2 Mean values of oxygen consumption with exposure to vibration at a constant acceleration-amplitude.

to note that the increases in metabolic oxygen consumption obtained with the subject exposed to vibration at frequencies of 2 Hz and 4 Hz were disproportionately less than the corresponding increases in values of pulmonary ventilation obtained during vibration exposure at the same frequencies. With exposure of the subject to constant acceleration vibration at frequencies of 8 and 10 Hz there were no significant changes in values of metabolic oxygen consumption over those obtained with the subject at rest.

In order to allow a comparison to be made of the metabolic energy expended by the subject during whole-body vibration with that expended by the pilot flying various aircraft, mean values of metabolic oxygen consumption have been converted to values of energy expenditure (unit, $kcal/m^2hr$). These are presented in Table 6.6 for eight subjects exposed to vibration at a constant acceleration amplitude and various frequencies.

(d) Carbon dioxide output

The results of measurements of carbon dioxide output obtained during this series of experiments are shown in Table 6.7 for eight subjects who were restrained and unrestrained in the vibration seat. It may be seen by reference to this table that for both conditions of the experiment (subject restrained and unrestrained) there was a moderate increase in the values of carbon dioxide production during vibration at frequencies of 2, 4 and 6 Hz over those values

Table 6.6 Metabolic energy expended by the subject during exposure to whole-body vibration at various frequencies. Mean values for eight subjects.

Frequency of vibration (Hz)	Mean metabolic energy expenditure ($kcal/m^2hr$) in the following conditions:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
2	48.2	56.5	56.0	48.3
4	48.1	60.7	58.9	44.2
6	50.0	62.3	59.4	46.7
8	46.8	46.9	45.3	42.1
10	46.7	48.4	49.2	47.3

obtained with the subject at rest prior to the vibration period. The maximum increase in carbon dioxide output was obtained after the first five minutes of vibration and thereafter declined towards control values at the end of the ten minute period of vibration exposure. The greatest change in carbon dioxide output was obtained with exposure of the subject to vibration at a frequency of 6 Hz and analysis has shown that this was significantly greater than values obtained with the subject at rest ($P = 0.001$). With exposure of the subject to vibration at frequencies of 2 and 4 Hz there was a moderate increase in carbon dioxide production after 5 minutes and 10 minutes exposure and the values obtained were significantly greater than those obtained during the period of

Table 6.7 Effect of whole-body vibration (constant acceleration-amplitude) upon carbon dioxide production in eight subjects exposed to vibration at frequencies 2 - 10 Hz in the restrained and unrestrained condition

Frequency of vibration (Hz)	Mean value of carbon dioxide output /(L/min STPD) in the following conditions:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	0.284	0.335	0.279	0.248
4	0.275	0.320	0.297	0.215
6	0.284	0.342	0.321	0.220
8	0.281	0.310	0.280	0.242
10	0.291	0.300	0.287	0.251
		UNRESTRAINED		
2	0.293	0.352	0.308	0.257
4	0.284	0.360	0.338	0.232
6	0.287	0.339	0.317	0.228
8	0.279	0.306	0.281	0.240
10	0.289	0.301	0.279	0.248

rest ($P = 0.001$). With exposure of the subject to vibration at frequencies of 8 and 10 Hz however there was no significant difference in values of carbon dioxide output obtained during the period of vibration over those values obtained with the subject at rest. There was no significant differences in the values for carbon dioxide output between the two conditions of the experiment in which the subject was restrained and unrestrained in the vibrating seat during vibration exposure.

(e) Respiratory exchange ratio

The results of measurements of Respiratory Exchange Ratio obtained in this series of experiments are presented in Table 6.8 for eight subjects exposed to vibration at a constant acceleration-amplitude, both in the restrained and unrestrained positions in the vibrating seat. It may be seen by reference to Table 6.8 that in both conditions of the experiment (i.e. with the subject restrained and unrestrained in the seat) there was a marked increase in values of respiratory exchange ratio (in some cases to values greater than unity) during the first five minutes of exposure of the experimental subject to vibration at frequencies of 2 and 4 Hz. These changes were highly significant ($P = 0.001$) when compared with values of respiratory exchange ratio obtained during the period of rest prior to vibration. Analysis has shown that at these frequencies where a change in Respiratory Exchange Ratio occurred, this was greatest after five minutes of exposure to vibration, after which there was a reduction in the value obtained towards the end of the vibration period. With vibration exposures at frequencies of 6, 8 and 10 Hz there were no significant changes in the value of Respiratory Exchange Ratio from those obtained during the rest period prior to vibration.

Table 6.8 Effects of whole-body vibration at constant acceleration amplitude on the Respiratory Exchange Ratio. Eight subjects exposed to vibration at frequencies of 2 - 10 Hz in the restrained and unrestrained condition

Frequency of vibration (Hz)	Mean value of Respiratory Exchange Ratio in the following conditions:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		RESTRAINED		
2	0.94	1.03	0.90	0.83
4	0.93	1.04	0.91	0.80
6	0.89	0.98	0.90	0.80
8	0.89	0.94	0.92	0.82
10	0.92	0.90	0.89	0.83
		UNRESTRAINED		
2	0.91	1.02	0.91	0.82
4	0.91	1.01	0.95	0.82
6	0.91	0.96	0.90	0.82
8	0.91	0.95	0.92	0.82
10	0.92	0.92	0.89	0.84

(f) Symptoms arising during whole-body vibration

As in the previous series of experiments, each subject was asked to complete a questionnaire at the end of each exposure to vibration at constant acceleration-amplitude. This questionnaire asked specifically for details of general comfort during the vibration run with particular emphasis on any symptom of discomfort experienced in the chest, abdomen, back, head and neck, pelvis or other anatomical site. The reports of discomfort arising during a total of 80 experimental vibration exposures are summarised in Tables 6.9 and 6.10 for eight subjects exposed to vibration at a constant acceleration-amplitude and frequencies of 2 - 10 Hz. The results in Table 6.9 show the number of reports of discomfort during the runs in which the subject was fully restrained in the vibrating seat, while in Table 6.10 results are given for the condition in which the subject was unrestrained in the seat.

It may be seen by reference to Tables 6.9 and 6.10 that in general terms, there were very few reports of discomfort by subjects exposed to vibration of the type used in this part of the study. In the conditions of the experiment where the subject was restrained and unrestrained in the vibrating seat there were, however, a few reports of discomfort in the chest and abdominal regions during exposure of the subject to whole-body vibration at a frequency of 6 Hz. In each case, however, the reporting subject stated that these symptoms of discomfort could be relieved by deliberate tensing of musculature of chest wall and abdomen. It should be re-emphasised at this stage that the subjects were repeatedly instructed to make no deliberate attempts to relieve their discomfort during the vibration period. The discomfort

Table 6.9 Summary of symptoms reported during whole-body vibration at constant acceleration-amplitude and frequencies of 2 - 10 Hz. Eight subjects restrained in the vibrating seat (each + represents one report of discomfort)

Symptom	Frequency of vibration (Hz) 2	4	6	8	10
	RESTRAINED				
General discomfort			++		
Discomfort or pain in chest			+		
Discomfort or pain in abdomen		+	+		
Discomfort or pain in back			++		
Discomfort or pain in head and neck				+	
Discomfort or pain in pelvis					

arising in some subjects during exposure to vibration at a frequency of 6 Hz was similar in nature but of less severity than that experienced at the same frequency (6 Hz) during the constant amplitude vibration experiments.

Of particular interest in the present context is the almost total absence of reports of discomfort during exposure of the subject to vibration at frequencies of 2 and 4 Hz. With exposure

Table 6.10 Summary of symptoms reported during whole-body vibration at constant acceleration-amplitude and frequencies of 2 - 10 Hz. Eight subjects unrestrained in the vibrating seat

Symptom	Frequency of vibration (Hz) 2	4	6	8	10
	UNRESTRAINED				
General discomfort			+++		
Discomfort or pain in chest			++		
Discomfort or pain in abdomen			+		
Discomfort or pain in back		+	++		
Discomfort or pain in head and neck					+
Discomfort or pain in pelvis	+				

to vibration at these frequencies it will be recalled that there was an increase in pulmonary ventilation to values greater than those obtained at rest, with a moderate degree of hyperventilation and hypocapnia. The absence of symptoms of discomfort during vibration at the frequencies causing the greatest respiratory changes contrasts with the findings of the previous experiments (constant amplitude series - reported in Chapter 4) where the subject experienced severe discomfort during exposure to the higher frequencies of vibration used in the study and where the greatest respiratory changes were also observed.

In the present series of experiments no subject reported any symptoms which could be attributed to hypocapnia at any of the frequencies of vibration used in the study.

6.4 Discussion

The experiments which have been described in this chapter confirm the findings of the few previous workers in this field (Dixon et al, 1961; Ernsting, 1961; Duffner et al, 1962) that whole-body vibration at a constant acceleration-amplitude and at certain frequencies causes an increase in the level of pulmonary ventilation in the experimental subject. Thus it has been shown that with vibration at an acceleration amplitude of $\pm$ 0.4 Gz and at frequencies of 2, 4 and 6 Hz there was an increase in minute volume ventilation to values greater than those obtained at rest. This increase in minute volume ventilation during the period of whole-body vibration occurred within ½ to 1 minute of the start of the vibration exposure, reached a maximum value during the first five minutes of vibration and thereafter, decreased in magnitude towards the end of the vibration period. The characteristics of the changes in pulmonary ventilation were similar to those reported by previous workers for vibration at a constant acceleration-amplitude although in the present series of experiments the magnitudes of the increases in pulmonary ventilation were somewhat less than those obtained by previous authors who used similar conditions of vibration.

In contrast to the findings of the previous series of experiments carried out in this investigation (using constant amplitude vibration) the changes in pulmonary ventilation in the present experiments were greatest at the lower frequencies used in the study (i.e. at 2, 4 and 6 Hz with constant acceleration-amplitude vibration as compared with 6, 8 and 10 Hz with constant amplitude vibration). The increase in pulmonary ventilation at the lower range of frequencies studied (2 and 4 Hz) was brought about almost exclusively by an increase in tidal volume, the respiratory frequency remaining virtually unchanged throughout the period of rest, vibration and recovery. This contrasts with the findings in the earlier series of experiments where exposure of the subject to vibration at a constant amplitude caused an increase in pulmonary ventilation at certain frequencies which was brought about partly by an increase in tidal volume and partly by an increase in respiratory rate.

Analysis of the data has shown that the greatest increase in pulmonary ventilation during the period of vibration at constant acceleration-amplitude occurred at a frequency of 6 Hz. This finding is similar to that of Duffner et al, 1962, who observed the greatest increase in pulmonary ventilation during exposure of their subjects to vibration at a constant acceleration-amplitude of $\pm$ 0.35 Gz and a frequency of 5 Hz. Since this is one of the dominant modes of resonance in the seated body, these authors offered this as an explanation for their findings. In that study, however, Duffner et al adduced evidence that true hyperventilation occurred with exposure of the subject to vibration at this frequency as there was an increase in the respiratory quotient to values greater than 1.0 and a modest fall in alveolar carbon dioxide concentration. By contrast, the findings of the present experiments clearly indicate that exposure of the subject to vibration at a frequency of 6 Hz did not induce hyperventilation or hypocapnia. Thus although the greatest change in pulmonary ventilation was obtained during vibration at a frequency of 6 Hz (during vibration mean pulmonary ventilation was 28.5% greater than values obtained at rest) there was a proportional increase in metabolic oxygen consumption during exposure to vibration at the same frequency (mean increase = 26.7% over resting values), virtually no change in the Respiratory Exchange Ratio and no reduction in end tidal carbon dioxide tension. It is likely that the respiratory changes observed in the subject exposed to vibration at a frequency of 6 Hz resulted as a consequence of increased metabolic activity during the period of vibration. It is noteworthy, that with the conditions of vibration used in the present study (acceleration = ± 0.4 Gz) no hyperventilation occurred in the exposed subject at a forcing frequency of 6 Hz although in a previous experiment (reported in Chapter 3) exposure to vibration at this frequency and an acceleration of ± 0.5 Gz caused quite marked hyperventilation. It is clear from this observation that the intensity of the imposed vibration stimulus is an important factor in the respiratory changes induced by whole-body vibration at this frequency and it is likely that the explanation for this difference lies in the fact that the vibration at lower intensity (acceleration ± 0.4 Gz) was of insufficient magnitude as to cause serious discomfort or pain in the subject. It should be noted that in the present experiments there were very few reports of discomfort during vibration exposure and those that did occur were of a comparatively minor nature only.

An important finding in the present series of experiments is that at certain frequencies, whole-body vibration at a constant acceleration-amplitude induced hyperventilation with hypocapnia. Thus it has been shown that exposure of the subject to vibration at a constant acceleration-amplitude and frequencies of 2 Hz and 4 Hz induced a moderate increase in values of pulmonary ventilation over those values obtained during the period of rest (mean increases at 2 Hz and 4 Hz were 19.6% and 19.9% respectively). With exposure to vibration at the same frequencies there was a small increase in metabolic oxygen consumption (mean increases over resting values for 2 Hz and 4 Hz were 9.7% and 9.6% respectively) although at these frequencies of vibration there was a greater increase in pulmonary ventilation than the corresponding relative increase in metabolic oxygen consumption. Further evidence for the occurrence of true hyperventilation is supported by a greater increase in carbon dioxide production than in oxygen uptake as reflected by values of the respiratory exchange ratio obtained during these conditions of vibration. The occurrence of hypocapnia in the subject exposed to vibration at frequencies of 2 Hz and 4 Hz was demonstrated by a moderate fall in end tidal carbon dioxide tension during the first five minute period of vibration exposure at these frequencies. It was observed that the hyperventilation and resulting hypocapnia occurred only during the first five minutes of vibration exposure at frequencies of 2 Hz and 4 Hz and that towards the end of exposure to vibration at these frequencies the increase in pulmonary ventilation was proportional to the relative increase in oxygen consumption. This contrasts with the findings of the previous experiments (using constant amplitude vibration) where hyperventilation and hypocapnia occurred at certain frequencies of vibration studied and was sustained throughout the entire period of vibration exposure. In their studies, Duffner et al (1962) observed a similar phenomenon during exposure of their subjects to whole-body vibration at constant acceleration-amplitude ($\pm$ 0.35 G) and frequencies of 2 - 7 Hz. The return of effective ventilation towards control values during the vibration period after initial hyperventilation suggested to these authors that there might be either a counteracting stimulus to hyperventilation or some form of adaptation to the vibration condition.

The results of this study show that after a certain period, exposure of the subject to whole-body vibration at constant acceleration-amplitude ($\pm$ 0.4 G) induced hyperventilation and hypocapnia at the lower frequencies studied (2 Hz and 4 Hz). This is in contrast to the findings of the previous series of experiments in which exposure of the subject to vibration at a constant amplitude induced the respiratory changes at the higher frequencies of vibration studied (6, 8 and 10 Hz). An explanation for the hyperventilation and hypocapnia observed in the constant amplitude vibration studies was advanced on the basis of sheer discomfort induced by vibration at high intensity. In this series of experiments (using vibration at a constant acceleration-amplitude) hyperventilation and hypocapnia which occurred at the lower end of the frequency range studied, was not accompanied by any discomfort. Similar changes have been described by Dixon et al (1961) who exposed normal subjects to positive near vertical movements of the trunk at frequencies of 0.5 and 0.8 Hz. They found that this procedure induced a considerable increase in pulmonary ventilation in the absence of any discomfort on the part of the subject and these authors suggested that these respiratory changes might be due to labyrinthine stimulation. In the studies carried out by Ernsting (1961) subjects were exposed to vibration at a constant acceleration (± 0.25 Gz) over the frequency range 1.7 to 9.5 Hz, and an increase in pulmonary ventilation with evidence of hyperventilation and hypocapnia was obtained with the subject exposed to vibration at the lower end of the frequency range studied. In that investigation as in the present experiments, there was no appreciable discomfort at the lower frequencies of vibration and the hyperventilation which occurred at these frequencies was also ascribed by this author to labyrinthine stimulation. It is possible that such a mechanism was responsible for the respiratory changes observed in the present series of experiments, but before advancing this hypothesis it is first necessary to consider and exclude a number of other factors which might have been responsible.

Attention has been drawn to the fact that exposure of the subject to low frequency (2 and 4 Hz) vibration at constant acceleration-amplitude (± 0.4 Gz) was not associated with either pain or discomfort at the frequencies of vibration during which hyperventilation and hypocapnia were observed. It is clear therefore that in contrast to the results obtained in the previous experiments where frank pain and discomfort occurred at the higher intensities of vibration studied (and during which marked hyperventilation and hypocapnia were observed) this cannot be advanced as the explanation for the observed respiratory changes. In common with both series of experiments (i.e. constant amplitude and constant acceleration vibration) there was in the present experiments no anxiety on the part of the subjects, all of whom were highly experienced in vibration procedures, and it is believed that this could not have been a factor contributing to the observed hyperventilation. A number of authors have considered the possibility that hyperventilation during whole-body vibration could arise as a result of stimulation of mechanoreceptors through mechanical distortion of tissues with a consequent reflex increase in pulmonary ventilation beyond the requirements of the body. Although such a mechanism cannot be excluded, it would be expected that the greatest degree of hyperventilation would arise in the vibration situation which gives rise to the greatest degree of mechanical movement of tissues and organs of the body - i.e. at resonance. As previously stated, one such resonance exists in the seated subject at a frequency of about 5 Hz and the results of the present study have shown that at a forcing frequency of 6 Hz there was considerable movement of certain tissues accompanied by slight but measurable discomfort on the part of the subject. At this frequency of vibration there was, however, no evidence of hyperventilation in the experimental subject and this would support the belief that stimulation of mechanoreceptors was not the mechanism responsible for the hyperventilation and hypocapnia induced by vibration at the lower frequencies studied.

One possibility which must be considered is that a proportion of the increase in pulmonary ventilation observed at certain frequencies during whole-body vibration at a constant acceleration-amplitude might have been due to the abdominal contents oscillating in and out of the thoracic cage during vibration and thus driving gas in and out of the lungs. In his investigations, Ernsting (1961) showed, however, that the volume of gas oscillating in and out of the respiratory tract in this way was considerably less than the volume of the anatomical dead space and it is unlikely therefore that such a process could contribute significantly to the production of hypocapnia.

It is very difficult, therefore, to advance an explanation for the respiratory changes observed in this study with exposure of the subject to whole-body vibration at a constant acceleration-amplitude. One possibility, however, remains - that at the lower frequencies in the range studied, whole-body vibration may induce vertical and rotational movements of the head of such magnitude as to cause stimulation of the labyrinth and reflex hyperventilation. Although there is no conclusive evidence for the existence of a reflex mechanism of this type causing an increase in pulmonary ventilation it is known that there is a wide distribution of vestibular reflexes. It is possible, therefore, that among the many reflexes associated with vestibular stimulation there may be a reflex mechanism causing hyperventilation in response to short duration linear and rotational acceleration of the head during certain conditions of whole-body vibration. To date, however, all previous attempts to demonstrate such a mechanism (Lamb and Tenney, 1966) by exposing the head of a subject directly to vibrations have not proved successful. Until more evidence becomes available any proposal that such a reflex mechanism is the cause of hyperventilation during certain conditions of vibration must, of course, remain entirely speculative.

With regard to the metabolic energy expended by the subject during exposure to whole-body vibration at constant acceleration it has been shown in this study that there was a moderate increase in oxygen consumption during vibration at frequencies of 2 Hz and 4 Hz. At these lower frequencies, considerable displacement of the vibrating platform was required in order to maintain an acceleration amplitude of 0.4 Gz and it is likely that the increase in oxygen consumption obtained during vibration resulted from the muscular effort required by the subject to maintain his posture in the face of violent shaking. This belief is reinforced by the finding that during vibration with the subject restrained by harness in the seat, the values of oxygen consumption were significantly lower at frequencies of 2 Hz and 4 Hz than values obtained when the subject was unrestrained by harness. The greatest increase in metabolic oxygen consumption occurred in the subject exposed to constant acceleration vibration at a frequency of 6 Hz and it is believed that this increase may have been brought about by muscular tensing on the part of the subject as an attempt to modify the transmission of vibration through the body or to reduce uncomfortable differential movement of various parts. It will be recalled that during exposure to vibration at a frequency of 6 Hz there were a few complaints of discomfort in chest and abdominal regions. The increase in oxygen consumption at this frequency could not have resulted from a requirement to maintain posture since the values of the respiratory variables were of the same magnitude in the experimental condition in which the subject was unrestrained (and free to adjust posture during vibration), as in the condition where he was firmly restrained by harness in the vibrating seat.

From a practical point of view, this part of the study has shown that exposure to vibration at an acceleration of $\pm$ 0.4 Gz and frequencies of 2 Hz and 4 Hz causes an increase in metabolic activity which is similar in magnitude to that obtained in the pilot flying various fixed wing and rotary wing aircraft in routine straight and level flight. With exposure to vibration of this type at a frequency of 6 Hz, however, there is a greater increase in metabolic energy expenditure during the period of vibration and this approximates in magnitude to the energy expended by the pilot of fixed wing or rotary wing aircraft engaged in more strenuous phases of flight (e.g. ascent, descent, instrument approach in fixed wing and hovering close to the ground in rotary wing aircraft).

CHAPTER 7

The influence of sitting posture on the respiratory effects of whole-body vibration at a constant acceleration-amplitude

7.1 Introduction

In the previous chapter, experiments were described in which the subject was exposed to whole-body vibration at a constant acceleration-amplitude ($\pm$ 0.4 Gz) whilst seated in an aircraft type seat mounted on the vibrator platform. In that study it was shown that exposure to vibration at frequencies of 2 Hz and 4 Hz caused a moderate increase in pulmonary ventilation which was a true hyperventilation with hypocapnia. The magnitude of the changes in pulmonary ventilation were, however, slightly less than those obtained by previous workers (Ernsting, 1961; Duffner et al, 1962) whose subjects were exposed to similar conditions of vibration but were seated in an upright posture either directly on the platform of the vibrator or on a simple seat attached thereon. This suggested therefore that the differences in the magnitude of the respiratory changes obtained in the experiments performed by previous workers and those obtained in the present series might be explained on the basis of a difference in sitting posture. There is some evidence that the response of man to whole-body vibration at or near resonant frequencies of the body, may be modified by the adoption of a slouched posture, or by leaning back in a reclining seat (Guignard, 1965) and it is believed that major resonance effects may be reduced by suitable posture and orientation of the seated man in relation to the direction of vibration. It was considered possible that the adoption of a semi-reclining posture (representative of that used in normal flight) might broaden the distribution of the force of vibration along the spinal axis in such a way that differential movement of parts of the body would be reduced, and the effects resulting from this movement correspondingly less.

In view of the practical interest in the sitting posture of aircrew required to operate in different flight conditions, it was considered that it would be worthwhile to measure the respiratory changes associated with exposure of the subject to vibration whilst seated in an upright posture, and to compare the results with those obtained during exposure of the subject to the same conditions of vibration, but seated in a semi-reclining posture. For this study it was decided to expose the seated subject to whole body vibration at a constant acceleration-amplitude (rather than at a constant displacement amplitude) since the results of the previous experiments had suggested that the respiratory changes associated with exposure to vibration of this type might be related more to movement of the subject's head (and stimulation of the labyrinth) rather than to the pain and discomfort induced by the vibration stimulus. In this part of the investigation, therefore, the respiratory effects of whole body vibration at a constant acceleration amplitude ($\pm$ 0.4 Gz) and at frequencies of 2, 4, 6, 8 and 10 Hz have been measured in five subjects who sat in an upright posture in a seat which was specially constructed for this purpose and mounted on the platform of the vibrator. The results of these measurements have been compared with those obtained during exposure of the subject to the same conditions of vibration but with him seated in a semi-reclining posture in a modified aircraft seat which was mounted on the vibrator platform. The results of this investigation are reported in this chapter of the thesis.

In the planning stages of the experiments it had been hoped that measurements would be taken of the vertical and rotational components of head movements during exposure of the subject to vibration in each sitting posture. It was found, however, by preliminary experimentation, that the magnitude of the accelerative force of each of these components of head movement during exposure to vibration at a constant acceleration of $\pm$ 0.4 G, and frequencies from 2 - 10 Hz was beyond the measuring capabilities of the electronic transducers which were available for this purpose. As an addition to the main experimental programme therefore, the vertical and rotational components of head movement were measured with the subject seated in each of the test postures, but with the intensity of vibration exposure reduced to an acceleration amplitude of $\pm$ 0.1 G. It was found by preliminary experiments that with vibration at this intensity accurate measurements of head movement could be obtained at forcing frequencies of 2, 4 and 6 Hz using the available transducers. The results of this additional experiment are also included in this chapter of the thesis.

7.2 Methods

In order to compare the respiratory effects of exposing the subject to whole-body vibration in each of two postures (upright and semi-reclining) two different seats were mounted in turn on the platform of the vibrator. For the experiments in which the subject was required to assume a semi-reclining posture, a modified aircraft ejection seat with its appropriate back pack and seat-pack was mounted on the vibrator. This seat was the same one as that used in previous experiments described in this thesis and details of its construction and nature have been given elsewhere. For the experiments in which the subject was required to adopt an upright posture a special seat was constructed and mounted on the platform of the vibrator. This experimental seat consisted of a rectangular shaped framework which was constructed from angle iron and bolted on to the platform of the vibrator by means of four mounting lugs welded on to each corner of the framework. A fibre-glass seat pack (the same one as that used with the modified aircraft seat) was inserted into the metal framework in such a way that its upper surface was horizontal to the floor upon which the vibrator was mounted. A footrest affixed to the front edge of the framework allowed the experimental subject to sit upright in a comfortable posture. No backrest was included in the construction of this seat.

Five subjects, each of whom had participated in the previous experiments took part in this investigation. Each subject wore a standard Royal Air Force pattern lightweight coverall, and an integral protective helmet Mk 2, and sat in either of the two seats mounted on the platform of the vibrator. For the experimental sessions in which the subject was required to adopt an upright posture he sat on the experimental seat which had been constructed for this purpose, and he was instructed to maintain his back as straight as possible, fixate his vision on a distant eye datum point and to keep his hands resting lightly on his knees throughout the period of vibration exposure. Similar instructions were given to the subject in the experimental sessions in which he was required to maintain a semi-reclining posture in the modified aircraft type seat. On this occasion, however, he was instructed to place his back firmly against the backpack mounted in the seat pan and thereby to assume a posture as close to that used by aircrew in flight as was possible. Each subject breathed room air from the experimental breathing circuit, which was the same as that used in the previous experiments. The nostrils were occluded by a suitable nose-clip. Expired gas was conducted by means of wide bore hose from the expiratory portion of the breathing circuit to a recording gas meter and then to gas collection equipment (a description of which has been given elsewhere). A continuous measurement was made of end tidal carbon dioxide concentration using an infra-red carbon dioxide meter, the sampling probe of which was inserted into the breathing circuit close to the lips of the subject. The output signal obtained from the recording head of the infra-red carbon dioxide meter was amplified and displayed on a single channel of an Esterline-Angus pen recorder. The acceleration-amplitude of the vibration measured at the seat of the subject during exposure at each forcing frequency was obtained using a variable resistance accelerometer (range $\pm$ 10 G), a suitable amplifier and pen recorder.

At various periods throughout the experimental procedure a collection was made of expired gas over a period of three minutes. In each case the collection was made in a Douglas bag and the contents of the bag were analysed for carbon dioxide and oxygen concentrations and the data obtained in this way were used to calculate metabolic oxygen consumption, carbon dioxide output and respiratory exchange ratio for various times during the experimental procedure. A more detailed description of the nature and mode of operation of the measuring equipment used in this study has been given elsewhere, together with the calibration procedures involved.

With each sitting posture (upright and semi-reclining) each subject was exposed to identical conditions of whole-body vibration at a constant acceleration-amplitude ($\pm$ 0.4 Gz) and at each of five different forcing frequencies (2, 4, 6, 8 and 10 Hz). The sitting posture adopted by the subject and the forcing frequency of vibration used in each experimental session was applied in a random fashion and none of the subjects was aware of the purpose of the experiment. Each experimental session consisted of a period of rest which lasted five minutes, a period of exposure to the chosen condition of vibration lasting ten minutes and a subsequent period of recovery from vibration which lasted five minutes. Measurements of pulmonary ventilation and end tidal carbon dioxide concentration were made continuously throughout the period of rest, vibration exposure and recovery. A collection of expired gas was made during the last three minutes of the rest period. During vibration two collections were made. The first was taken between minute 2 and minute 5 of vibration and the other between minute 7 and minute 10 of vibration (hereafter these are referred to as the five and ten minute samples respectively). A final collection of expired gas was obtained during the last three minutes of the recovery period.

Measurement of head movement

In addition to the main experiments, a separate study was made of the vertical and rotational components of head movement during exposure of the subject to vibration at a constant acceleration-amplitude and with him seated in each of two sitting postures (upright and semi-reclining). For technical reasons which have been explained in the introductory paragraphs of this chapter, the vibration exposure used in this part of the study was reduced in intensity. Three subjects were exposed to whole-body vibration at a constant acceleration-amplitude ($\pm$ 0.1 Gz) and at frequencies of 2, 4 and 6 Hz, seated first in an upright posture in the vibration seat and then in a semi-reclining posture. The head movements obtained with each posture were measured and compared using two accelerometers, each mounted on either side of a protective helmet worn by the subject during each vibration exposure. One accelerometer (range $\pm$ 5 G), mounted on the right-hand side of the protective helmet recorded movement in the vertical plane with the head erect, whilst the other accelerometer (range $\pm$ 50 radians/sec^2) mounted on the left-hand side of the protective helmet recorded movement of the head only in the rotational axis. These accelerometers were mounted as close to the right and left ears of the subject as was possible and the protective helmet was fitted very carefully using standard aircrew fitting procedures. The output signals from each accelerometer were fed on to separate channels of a magnetic tape recorder and were later analysed using a Digital Transfer Function Analyser (Type JM 1600) in conjunction with a Mechanical Reference Synchroniser (Type JX 1606), both manufactured by the Solartron Electronics Group Ltd. With this instrument, the signal recorded from each transducer monnted on the protective helmet worn by the subject, was compared with a generated reference signal with respect to the relative amplitude.

The relative amplitude of the test signal was displayed on a digital voltmeter as a Root Mean Squared (RMS) voltage. The accelerative force for each component of head movement (vertical and rotational) obtained with the subject seated in a semi-reclining posture to that obtained with the subject seated in an upright position was measured for each of the conditions of vibration at frequencies of 2 Hz, 4 Hz and 6 Hz. From this data calculation was made of the relative amplitudes of vertical linear and rotational head movement during vibration in a semi-reclining posture to those obtained during vibration in an upright posture.

The reference signal for this measurement was obtained by attaching a thin strip of metal to the shaft of the motor drive to the eccentric of the vibration generator. With each revolution of the shaft drive the rotating metal strip interrupted a beam of light which was focussed on to a photo electric cell. The intermittent signal thus obtained was suitably amplified and fed at an appropriate voltage on to one channel of a magnetic tape recorder. The recorded signal was later fed into the Mechanical Reference Generator during the subsequent analysis of vertical and rotational head movements.

7.3 Results

(a) Pulmonary ventilation

The results obtained for minute volume ventilation for five subjects exposed to whole-body vibration at frequencies of 2 - 10 Hz and a constant acceleration-amplitude (± 0.4 Gz) are given in Table 7.1. This table gives the mean values obtained for minute volume ventilation with the subject seated on the vibrator seat in an upright posture and in a semi-reclining posture.

Table 7.1 Mean values of minute volume ventilation in five subjects at rest, during vibration and during recovery, whilst seated in upright and semi-reclining postures

Frequency of vibration (Hz)	Minute volume ventilation (Litre BTPS) during:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		SEMI-RECLINING POSTURE		
2	9.46	12.26	10.45	8.91
4	9.38	12.40	11.56	8.37
6	9.17	14.21	12.55	8.67
8	9.44	10.06	9.84	9.17
10	9.09	9.80	9.82	9.53
		UPRIGHT POSTURE		
2	9.52	14.84	11.76	8.32
4	8.91	13.32	11.14	8.56
6	9.02	14.76	12.83	8.05
8	9.27	10.18	9.95	8.82
10	9.44	9.89	9.96	8.40

It may be seen from Table 7.1 that with exposure to vibration at frequencies of 2, 4 and 6 Hz there was a marked increase in pulmonary ventilation during the vibration period, in both conditions of the experiment where the subject was seated either in an upright or a semi-reclining posture. The increase in pulmonary ventilation at each of these frequencies of vibration was greatest at the beginning of the exposure and gradually declined in magnitude towards the end of the period of vibration. For both conditions of the experiment (subject in an upright and semi-reclining posture), the greatest increase in minute volume ventilation occurred with exposure of the subject to vibration at a frequency of 6 Hz. In those exposures in which the subject sat on the vibrator seat in an upright posture the increases in pulmonary ventilation at frequencies of 2 Hz and 4 Hz were greater than those obtained at the same frequencies but with the subject seated in a semi-reclining posture ($P = 0.001$). With exposure to vibration at a frequency of 6 Hz there were, however, no significant differences detected in the values of minute volume ventilation for the conditions in which the subject sat upright or in a semi-reclining posture.

The values of respiratory frequency obtained for each exposure to vibration at various frequencies and for the two conditions of posture are summarised in Table 7.2. It may be seen from this table that no significant change occurred in the

Table 7.2 Mean values of respiratory frequency with the subject at rest, during exposure to vibration and during recovery. Five subjects seated in an upright and semi-reclining posture

Frequency of vibration (Hz)	Respiratory frequency (breaths/min) during:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		SEMI-RECLINING POSTURE		
2	11.8	12.0	11.6	10.2
4	12.3	12.6	11.8	11.2
6	12.4	11.9	12.1	11.8
8	12.7	13.1	12.9	12.2
10	11.8	12.1	12.3	11.9
		UPRIGHT POSTURE		
2	12.5	11.9	12.1	11.7
4	12.1	12.0	11.6	12.2
6	11.7	11.1	10.9	10.7
8	11.8	12.2	12.6	12.0
10	11.6	12.1	11.8	12.4

rate of breathing during the vibration or recovery periods for either conditions of posture, and it is concluded therefore, that the increases in minute volume ventilation obtained with exposure of the subject to certain frequencies of vibration were brought about by an increase in tidal volume.

(b) End tidal carbon dioxide tension

Calculations of the mean values of end tidal carbon dioxide tension were made from the measured values of end tidal carbon dioxide concentration obtained throughout the experimental procedure. The mean values obtained with the subject at rest, after five minutes and ten minutes exposure to vibration at various frequencies and during recovery are presented in Table 7.3 for the conditions of the experiment in which the subject was seated in an upright and in a semi-reclining posture. It may be seen from this table that exposure to vibration with the subject seated in an upright and semi-reclining posture caused a reduction in end tidal carbon dioxide tension which was greatest at the start of vibration and at the lower frequencies of vibration (2 Hz and 4 Hz). The mean changes induced in the end tidal carbon dioxide tension were highly significant ($P = 0.001$) at those frequencies although there was no significant difference in the changes associated with each of the two postures used in the experiment.

(c) Metabolic oxygen consumption

The mean values of metabolic oxygen consumption obtained with the subject at rest, during exposure to vibration for five and ten minutes duration and during subsequent recovery, are presented in Table 7.4 for the conditions of the experiment in which the subject was seated on the vibrator in an upright and a semi-reclining posture. It may be seen from this table that

Table 7.3 The effect of whole-body vibration upon end tidal carbon dioxide tension during exposure of the subject seated in an upright and a semi-reclining posture

Frequency of vibration (Hz)	Mean value of end tidal carbon dioxide tension (mm Hg) during:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		SEMI-RECLINING POSTURE		
2	39.4	34.1	37.1	39.2
4	39.5	34.2	38.1	39.3
6	39.8	39.4	38.8	39.0
8	40.1	39.3	38.7	40.2
10	40.0	39.2	39.0	39.5
		UPRIGHT POSTURE		
2	40.1	34.6	36.5	38.7
4	38.9	33.1	37.5	39.2
6	39.5	38.7	39.0	39.0
8	38.8	39.2	39.0	38.9
10	40.4	39.6	38.7	39.3

there was an increase in metabolic oxygen consumption during the periods of vibration exposure at frequencies of 2, 4 and 6 Hz. For both conditions of posture the values of metabolic oxygen consumption obtained at those frequencies of vibration were significantly greater than those obtained during the control period of rest prior to vibration ($P = 0.001$). In each case the increase in the value of metabolic oxygen consumption was greatest at the start of the vibration exposure and thereafter declined towards the end of the vibration period. Analysis has shown that the increase in values of metabolic oxygen consumption obtained during exposure of the subject to vibration at frequencies of 2 Hz and 4 Hz was significantly greater when the upright posture was adopted than when a semi-reclining posture was adopted ($P = 0.001$). This difference in the magnitude of the changes in value of oxygen consumption with posture were not significant with exposure of the subject to vibration at a frequency of 6 Hz. It may also be seen from Table 7.4 that the greatest change in the value of oxygen consumption occurred with exposure to vibration at a frequency of 6 Hz in both conditions of posture.

(d) Respiratory exchange ratio

The results of the measurements of Respiratory Exchange Ratio obtained in this series of experiments for the subject exposed to various conditions of vibration in two different sitting postures are shown in Table 7.5. It may be seen from this table that with the subject seated in both the upright and semi-reclining postures exposure to vibration caused an increase in the Respiratory Exchange Ratio at forcing frequencies of 2 Hz and 4 Hz only. With exposure to vibration at all other frequencies there was no difference in the values of the Ratio between conditions of rest, vibration exposure and subsequent recovery. At those frequencies where a change in the Ratio occurred with vibration exposure, the

Table 7.4 Effects of whole-body vibration on metabolic oxygen consumption in five subjects seated in an upright and a semi-reclining posture

Frequency of vibration (Hz)	Mean value of metabolic oxygen consumption (Litre/min STPD) in the following conditions:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		SEMI-RECLINING POSTURE		
2	0.304	0.380	0.342	0.307
4	0.319	0.343	0.339	0.290
6	0.320	0.396	0.343	0.285
8	0.313	0.317	0.306	0.294
10	0.305	0.313	0.310	0.3
		UPRIGHT POSTURE		
2	0.318	0.435	0.384	0.287
4	0.315	0.378	0.355	0.280
6	0.329	0.409	0.351	0.298
8	0.325	0.324	0.312	0.284
10	0.328	0.337	0.326	0.304

maximum increase was obtained after an exposure of five minutes after which it declined towards the end of the period of vibration. For both conditions of posture the Respiratory Exchange Ratio exceeded unity during the first five minutes of the exposure of the subject to whole-body vibration at frequencies of 2 Hz and 4 Hz. Analysis has shown furthermore, that there were no significant differences in the values of Respiratory Exchange Ratio

Table 7.5 Effects of whole-body vibration on the Respiratory Exchange Ratio in five subjects seated in an upright and a semi-reclining posture

Frequency of vibration (Hz)	Mean value of Respiratory Exchange Ratio in the following conditions:			
	Rest	After 5 min vibration	After 10 min vibration	Recovery
		SEMI-RECLINING POSTURE		
2	0.87	1.04	0.98	0.79
4	0.89	1.03	0.96	0.74
6	0.85	0.89	0.92	0.82
8	0.87	0.91	0.89	0.85
10	0.91	0.90	0.88	0.83
		UPRIGHT POSTURE		
2	0.88	1.03	1.00	0.83
4	0.91	1.02	0.99	0.78
6	0.82	0.89	0.90	0.85
8	0.90	0.95	0.94	0.84
10	0.87	0.86	0.91	0.87

which could be accounted for by the posture adopted by the experimental subject.

(e) Vertical and rotational components of head movement

Measurements of the vertical linear and rotational components of head movement were obtained with exposure of three experimental subjects to whole-body vibration at a constant acceleration-amplitude ($\pm$ 0.1 Gz) and at frequencies of 2, 4 and 6 Hz. The results of this part of the investigation are summarised in Table 7.6, and are presented as a ratio of the amplitude of each component of head movement obtained with the subject exposed to vibration in a semi-reclining posture, to that obtained with the subject vibrated in an upright posture.

Table 7.6 Ratio of the relative amplitude of each component of head movement obtained with the subject vibrated in a semi-reclining posture, to that obtained with the subject vibrated in an upright posture. Results obtained from three subjects (S1, S2 and S3)

Frequency of vibration (Hz)	Ratio = Amplitude of head movement component - (subject semi-reclining) / Amplitude of head movement component - (subject upright)							
	Vertical component				Rotational component			
	S1	S2	S3	(mean)	S1	S2	S3	(mean)
2	1.06	1.22	1.05	(1.11)	0.82	1.08	0.80	(0.90)
4	0.71	1.05	1.03	(0.93)	0.85	1.05	1.09	(0.99)
6	0.77	0.94	1.00	(0.90)	0.84	0.85	1.21	(0.97)

It may be seen by reference to Table 7.6 that in the three subjects studied, there was a large variation in the ratio of vertical and rotational components of head movement obtained with the two conditions of posture. From the results obtained in this part of the study, it may be stated that there was no evidence that the adoption of an upright posture during the conditions of whole-body vibration caused any significant changes in either the vertical or rotational components of head movement over those obtained with the subject vibrated in a semi-reclining posture. These results would support the belief that for the conditions of whole-body vibration used in this part of the study (acceleration-amplitude $\pm$ 0.1 Gz, frequencies 2, 4 and 6 Hz) the adoption of a semi-reclining posture of the type normally employed by air-crew in flight would be unlikely to reduce the magnitude of the stimulus applied to the labyrinth from that which would be obtained with the subject in an upright seated posture. While these findings are related only to exposure of the subject to low intensity vibration (acceleration-amplitude = $\pm$ 0.1 Gz) it is believed that they would apply equally to conditions of whole-body vibration at a greater intensity (acceleration-amplitude = 0.4 Gz) since Guignard (1965) has shown that at or near resonant frequencies the transmissibility from seat-to-head during vibration is virtually unchanged at higher intensities. The seat-to-head transmissibility obtained in the subject during exposure to low intensity vibration has been calculated and is shown in Table 7.7 for the three forcing frequencies used in this part of the experiment. Also shown in this table is the transmissibility from seat to head obtained by Guignard (1965) for vibration of the same intensity (acceleration $\pm$ 0.1 G) as that used in the present study and for a higher level of intensity ($\pm$ 0.5 G) comparable to that used in the main experimental programme.

It may also be seen from this table that maximum values for seat-to-head transmissibility were obtained with exposure of the subject to vibration at a frequency of 4 Hz in the present studies and in those conducted by Guignard. This indicates a resonance of the head on the shoulders at or near this frequency of vibration.

Table 7.7 Seat-to-head transmissibility in the subject exposed to whole-body vibration at various frequencies and intensities. A comparison of the results obtained in the present experiments with those obtained by Guignard (1965)

Source	Acceleration-amplitude of vibration (± Gz)	Posture	Seat-to-head transmissibility at frequencies of (Hz) : 2	4	6
Guignard (1965)	0.1	Upright	1.01	1.90	1.81
"	0.5	Upright	1.02	2.11	1.72
Present study	0.1	Upright	1.01	2.60	2.2
"	0.1	Semi-reclining	1.12	2.50	1.91

It may be seen by reference to Table 7.7 that the values of seato-to-head transmissibility obtained during exposure of the subject to vibration at frequencies of 2, 4 and 6 Hz and an acceleration amplitude of ± 0.1 Gz were similar in magnitude in both studies (Guignard, 1965, and the present experiments).

It may also be seen that at those frequencies there was little change in values of seat-to-head transmissibility with exposure to vibration at a higher intensity (acceleration-amplitude = $\pm$ 0.5 Gz). These results support the belief that for the vertical linear component at least, it is unlikely that exposure of the subject to higher intensities of vibration would greatly affect the magnitude of head movements. They also allow the results obtained for head movements in the present studies (which for technical reasons were measured at a reduced intensity of vibration) to be carried over with reasonable confidence to the conditions of vibration used in the main experiments (i.e. at an acceleration-amplitude of $\pm$ 0.4 Gz).

7.4 Discussion

In the experiments which have been described in this chapter the subject was exposed to whole-body vibration at a constant acceleration amplitude ($\pm$ 0.4 Gz) and frequencies of 2 - 10 Hz. Measurements were made of the respiratory changes associated with exposure of the subject to vibration at each frequency whilst he was seated first in an upright posture and then in a semi-reclining posture. In general, the observed respiratory changes were similar in nature to those obtained in a previous study (reported in Chapter 6) where the subject was exposed to the same conditions of vibration, although there were a number of minor differences related to sitting posture. Thus in the present study it has been shown that with exposure to whole-body vibration at frequencies of 2 Hz and 4 Hz there was a moderate increase in pulmonary ventilation in the subjects who adopted a semi-reclining posture during the period of vibration and a larger increase in pulmonary ventilation in the subjects who adopted an upright posture during vibration. In both conditions of the experiment the increase in pulmonary ventilation was observed soon after the start of vibration exposure reached a maximum value after about five minutes of vibration and thereafter declined in magnitude towards the end of the period of vibration. In those conditions of the experiment where an increase in pulmonary ventilation occurred, this was brought about by an increase in tidal volume, the respiratory rate remaining virtually unchanged during the periods of rest, vibration and subsequent recovery.

Analysis of the data obtained in this study has shown that in both conditions of the experiment (i.e. with the subject in an upright and semi-reclining posture) exposure to vibration at frequencies of 2 Hz and 4 Hz induced a moderate degree of hyper-ventilation and hypocapnia. Thus the relative increase in pulmonary ventilation which was produced at these frequencies of vibration was greater than the corresponding relative increase in metabolic oxygen uptake. Although the magnitude of the values of pulmonary ventilation obtained during exposure of the subject to vibration at frequencies of 2 Hz and 4 Hz were greater with him seated in an upright posture, than with him seated in a semi-reclining posture, the increase in values of metabolic oxygen consumption were correspondingly greater in the former condition of the experiment and the degree of hyperventilation induced by vibration was of similar magnitude with both conditions of posture. This is supported by the observation that the degree of hypocapnia obtained during vibration (as evidenced by the measurements of end tidal carbon dioxide tension during the experiment) was almost identical for both conditions of posture. Also, the measurements showed that the greater increase in carbon dioxide output than in oxygen uptake (as reflected by the values of respiratory exchange ratio) during vibration at frequencies of 2 Hz and 4 Hz was no different for the two conditions of posture.

With exposure of the subject to whole-body vibration at a frequency of 6 Hz there was a marked increase in pulmonary ventilation both with the subject seated upright and in a semi-reclining posture during vibration. With both conditions of posture the relative increase in pulmonary ventilation was in proportion to the relative increase in metabolic oxygen uptake and at this frequency (6 Hz) no evidence of hyperventilation or hypocapnia was obtained for either condition. It was also observed that the increases both in pulmonary ventilation and metabolic oxygen consumption observed at this frequency of vibration, were similar in magnitude for both conditions of posture.

For both conditions of posture, exposure of the subject to vibration at frequencies of 8 Hz and 10 Hz caused no significant changes in pulmonary ventilation or gaseous exchange from those obtained during the periods of rest and recovery.

Thus it would appear from the results of this study that whilst the adoption of a semi-reclining sitting posture during vibration may induce smaller changes in pulmonary ventilation from those obtained with the subject in an upright posture, it has no effect on the degree of hyperventilation and hypocapnia induced by the vibration at certain frequencies. It is believed that the higher values for pulmonary ventilation and metabolic oxygen consumption obtained with exposure of the subject to vibration in the upright sitting posture may be related to the metabolic activity of the subject required to maintain posture during the vibration exposure. It will be recalled that at frequencies of 2 Hz and 4 Hz large displacement amplitudes were required to maintain the vibration at a constant acceleration of $\pm$ 0.4 Gz and it was noticed during the experimental procedures that the subject seated upright in the vibrator seat required much more effort to retain his posture during vibration than when he was seated in a semi-reclining posture. It is likely that the differences in sitting posture and the consequent muscular effort required by the subject to maintain that posture may also explain the differences in the results for pulmonary ventilation obtained in a previous experiment in this series and those obtained by previous workers in this field (Ernsting, 1961; Duffner et al, 1962), for similar conditions of vibration exposure. It will be recalled that the subjects used by those previous authors sat upright either directly on the platen of the vibrator or on a simple seat attached to the vibrator whilst in previous experiments described in this thesis the subjects were exposed to vibration in a semi-reclining posture in an aircraft type seat mounted on the vibrator.

The finding that the two different postures used in this study have little effect on the hyperventilation and hypocapnia induced by vibration at certain frequencies and intensities has an important practical application in the field of aviation. Thus it has been suggested that aircrew exposed to whole-body vibration in flight might be protected to a certain extent from the respiratory disturbances induced by the vibration by virtue of the fact that they are required to sit in a semi-reclining posture in most typical aircraft seats. It was postulated that the adoption of a semi-reclining posture might distribute the vibration over a larger area of the body in such a way as to protect the head from differential movement during vibration. If it is accepted that whole-body vibration of a certain type may induce hyperventilation and hypocapnia in the subject as a result of a reflex due to stimulation of the labyrinth, then it could be postulated that reduction in head movements during vibration might also reduce the associated respiratory changes. The results of this study have shown, however, that vertical linear and rotational head movements are of virtually the same magnitude in the upright and in the semi-reclining posture during exposure of the subject to whole-body vibration at an acceleration of $\pm$ 0.1 Gz and frequencies of 2 Hz, 4 Hz and 6 Hz. Arguments have been put forward in support of the belief that this is also true for exposure of the subject to vibration at the higher intensity used in the study (acceleration-amplitude = $\pm$ 0.4 Gz). It is concluded, therefore, that from a practical point of view the sitting posture adopted by an aircrew member during exposure to certain conditions of in-flight vibration would have no effect on the degree of hyper-ventilation or hypocapnia which may be induced by that vibration.

CHAPTER 8

General Discussion of the Results

Part I - Pulmonary ventilation and gaseous exchange

Part II - Metabolic oxygen consumption

CHAPTER 8

General Discussion of the Results

In the field of aviation medicine there is considerable interest in the physiological effects of low frequency structure-borne whole-body vibration in man. This was originally brought about by the requirement for certain military aircraft to operate at high speed and low level in conditions of meteorological turbulence. In-flight conditions of this type may induce short duration accelerations in the aircraft, which resemble mechanical noise with superimposed quasi-steady state vibrations due to air-frame structural response. To the aviation physiologist vibrations produced in aircraft flying in these conditions are of particular interest since they present at frequencies below about 15 Hz, at which both human body resonances and major aircraft modes are excited into large amplitude oscillations. The presence of mechanical vibrations of this type becomes of concern when they reach such intensity as to disturb the aircraft itself, or adjacent structures and in particular where they represent a threat to comfort, health or efficiency in aircrew.

Although there have been comparatively few studies on the physiological disturbances brought about by structure borne vibration in the low frequency range, it is known that they may affect man in a variety of different ways. A number of these disturbances may occur singly or may be compounded with other stresses liable to be encountered during certain types of flight - for example, acceleration, noise, heat and high work load. In the field of aviation medicine it is of great practical importance therefore, to have knowledge of the physiological disturbances induced in man by exposure to whole-body vibration so that medical advice may be given with respect to the design of aircraft and personal protective systems. This is required in order to improve the comfort, well-being and safety of aircrew operating in conditions of stressful flight.

The experiments which have been reported in this thesis were carried out in order to advance knowledge of some of the physiological effects of low frequency structure-borne whole-body vibration in man. In particular, two areas of disturbance have been investigated - that relating to the effects of vibrations on pulmonary ventilation and that relating to the increased metabolic activity induced by low frequency whole-body vibration. Although any separation of these two disturbances of respiratory function in man must be artificial, each presents a distinctive practical problem to aircrew required to operate in conditions of in-flight vibration. For this reason, a discussion of the experimental results obtained in this investigation and their significance in the field of aviation medicine has been separated into two parts - one concerning the effect of whole-body vibration on pulmonary ventilation and gaseous exchange, and the other concerning, more specifically, the effects on metabolic oxygen consumption in man.

PART I

Pulmonary ventilation and gaseous exchange

The experiments carried out in this investigation have demonstrated very clearly that at certain frequencies and amplitudes whole-body vibration induced an increase in pulmonary ventilation. When the amplitude of displacement of vibration was held constant there was a greater increase in pulmonary ventilation at the higher frequencies than at the lower ones investigated, whilst when the peak acceleration of the applied vibration was kept constant, the reverse held true. Thus it would appear that this phenomenon is neither solely acceleration nor amplitude dependent.

In the conditions of the experiment in which vibration at a constant amplitude was applied to the buttocks of the seated subject, there was a marked increase in pulmonary ventilation during the period of exposure to vibration at frequencies of 6, 8 and 10 Hz with the maximum changes occurring at the highest forcing frequency (10 Hz) used in this study. The results have indicated that at these frequencies of vibration where a change in minute volume ventilation occurred, the increase was rapid in onset after the start of the vibration, in most cases reached a maximum after about five minutes vibration and thereafter declined in magnitude towards the end of the ten minute vibration period.

It was found that the increase in minute volume ventilation induced by exposure of the subject to vibration at a constant amplitude was brought about by an increase in both tidal volume and respiratory rate. After the onset of vibration at frequencies of 6, 8 and 10 Hz there was a moderate increase in values of tidal volume which was sustained throughout the entire period of vibration. The respiratory frequency on the other hand increased shortly after the onset of vibration, reached maximum values after about five minutes of vibration exposure and thereafter declined in magnitude towards the end of the period of vibration.

One of the most important findings in this part of the study was that whole-body vibration at certain frequencies and amplitudes may induce quite severe hyperventilation and hypocapnia in the experimental subject. Thus during the part of the investigation in which vibration at a constant amplitude was applied to the buttocks of the seated subject, it was noted that the relative increase in pulmonary ventilation at the higher frequencies studied was greater than the corresponding relative increase in metabolic oxygen uptake. These measurements suggested that there was true hyperventilation at these frequencies of vibration and this conclusion was supported by the greater increase in carbon dioxide output than in oxygen uptake as reflected by the values of the respiratory exchange ratio during vibration. The reduction of pulmonary ventilation and respiratory exchange ratio in the recovery period below their respective control values, in the experiments in which pulmonary ventilation was raised during vibration, adds weight to the hypothesis that there was actual hyperventilation in these circumstances. The determinations of end tidal carbon dioxide tension demonstrated again, that under certain circumstances, whole-body vibration can cause very marked hypocapnia. In three of the subjects, each of whom developed well marked symptoms of hypocapnia on exposure to whole-body vibration at a constant amplitude and at a frequency of 8 Hz, the end tidal carbon dioxide tension fell to a value below 28 mm Hg after only three minutes of vibration. These findings confirm the previous reports in the literature (Dixon et al, 1961; Duffner et al, 1962; Ernsting, 1961), which show that exposure of the human subject to whole-body low frequency vibration may induce an increase in pulmonary ventilation at certain frequencies and intensities. Although in previous reports evidence has been adduced that whole-body vibration may cause moderate to severe hyperventilation and hypocapnia in certain subjects (Ernsting, 1961; Dixon et al, 1961; Duffner et al, 1962), the exact mechanism responsible for these respiratory changes was not clear.

In the present series of experiments a number of possible explanations for the respiratory changes during exposure to whole-body vibration at a constant displacement amplitude, were considered in detail. Thus it was believed that one possible mechanism - anxiety in the experimental subject - was not a factor in the causation of hyperventilation and hypocapnia during the period of vibration exposure, since all the subjects used in the experiment were highly experienced in the procedures involved. Also, in the questionnaire completed by each subject at the end of the period of vibration, all denied that there was any anxiety or apprehension present. It will be recalled that early workers in this field advanced this as a possible factor in the production of hyperventilation during vibration exposure of experimental subjects.

A second possible explanation for the respiratory changes during whole-body vibration was also considered. A number of authors suggested that the phenomenon may arise as a reflex due to stimulation of certain non-specific or specific mechanoreceptors situated in various parts of the body. The existence of such a reflex mechanism as a cause of hyperventilation is highly speculative, and all previous attempts to demonstrate it have failed (Lamb and Tenney, 1966). The results of the experiments carried out in the investigation support the view that such a reflex mechanism, if it exists, is not the prime cause of the hyperventilation and hypocapnia. Thus it was argued that if such a mechanism was responsible, the greatest effect on ventilation might be expected with the conditions of vibration giving rise to maximum distortion and differential movement of tissues containing the alleged mechanoreceptors, i.e. at a major mode of body resonance. In the present investigation, however, it was shown that the greatest degree of hyperventilation occurred with exposure of the subject to vibration, not at the resonant frequencies of the body, but at frequencies considerably higher than those known to induce body resonance.

Observations made during the present series of experiments point to the fact that hyperventilation which occurs during exposure of the subject to whole-body vibration is more likely explained on the basis of sheer discomfort induced by the vibration movement at certain frequencies and intensities. This explanation was one advanced by Ernsting (1961) for the marked hyperventilation and hypocapnia induced in his subjects by whole-body vibration similar in nature to that used in the present experiments. In the experiments carried out by Ernsting, and in these reported in this thesis, the frequencies and intensities of vibration which caused the greatest change in ventilation were also those which induced the greatest degree of pain and discomfort in the experimental subject. It is generally accepted that pain, or acute discomfort, may cause hyperventilation and hypocapnia in a subject, and it is believed that the discomfort associated with the conditions of whole-body vibration used in this study was of sufficient magnitude as to explain the respiratory effects.

There are a number of reports in the literature testifying to the acute discomfort associated with whole-body vibration encountered in various forms of transport as well as in laboratory experimental conditions, and it is well known to aircrew operating helicopters that low frequency vibrations occurring in the aircraft can give rise to abdominal and chest discomfort, after a relatively short period of exposure. There was, therefore, considerable interest in the possibility that the use of a restraining harness of the type used in fixed wing and rotary wing aircraft might help to suppress the pain and discomfort associated with whole-body vibration and might in turn reduce or eliminate the undesirable respiratory changes. In addition to protecting the wearer against severe forces of crash landing or assisted escape from aircraft, safety harnesses are known to provide a certain measure of protection against the severe low frequency oscillation of flight through turbulence. In the present experiments the respiratory effects of whole-body vibration were studied in subjects who were fully restrained in the ejection seat mounted on the vibrator platform using a modern harness system which, during the period of vibration, provided excellent restraint in all geometrical axes. The results obtained in this part of the study were compared with those obtained during vibration exposure with the subject seated in the ejection seat on the vibrator without any form of harness restraint.

A comparison of the results obtained from that study showed quite clearly that torso restraint in the subject seated on the vibrator failed to reduce the pain and discomfort associated with whole-body vibration at a constant amplitude of displacement, and at the higher frequencies studied. Furthermore, the increase in pulmonary ventilation, and the production of hyperventilation and hypocapnia at these frequencies occurred in both conditions of the experiment, i.e. with the subject restrained and unrestrained in the vibrating seat.

It was clear from these studies that even a modern harness system giving excellent restraint of the torso in the vibrating seat was, however, inadequate in the provision of support of the body in the anatomical sites where pain is experienced by the subject exposed to certain conditions of whole-body vibration. It has been known for centuries that resonant conditions within the body may be suppressed by rigid or semi-rigid bindings, and tight strapping has been practised in past times by Arab riders of fast dromedaries and is also practised by some racing motorists, motor cyclists and riders of bob-sleighs. Although this principle has not yet been adopted in aviation it was believed that provision of a suitable garment which offered external support to the abdomen and chest during whole-body vibration, might help to reduce the discomfort and pain in these areas during vibration and might also reduce the degree of hyperventilation and hypocapnia induced at certain frequencies of vibration. In the experiments reported in Chapter 5 of this thesis, a study was made of the modifying effects of wearing a standard item of aircrew equipment on the respiratory changes induced by whole-body constant amplitude vibration. The results obtained in that part of the investigation showed that the increase in pulmonary ventilation brought about by exposure to whole-body vibration at the higher frequencies studied (6, 8 and 10 Hz) was greatly reduced when the subject wore a garment which gave support to both abdomen and chest. Furthermore, it was demonstrated that when this garment was worn during the period of vibration exposure, the marked hypocapnia induced by vibration at certain frequencies in the unprotected subject was either eliminated or very greatly reduced. At those frequencies of vibration where the unprotected subject suffered considerable discomfort and pain in the abdomen and chest during whole-body vibration, wearing of the suit also eliminated or greatly reduced this. The results of this part of the investigation reinforced the belief that pain and discomfort in the chest and abdomen, experienced by the subject during exposure to constant amplitude whole-body vibration, is the most likely explanation for the hyperventilation and hypocapnia observed at the same forcing frequencies. It was believed that the application of external support to the abdomen prevented painful oscillation of the viscera during vibration and similar support to the upper torso prevented upwards and downwards movement of large muscle masses (e.g. pectoral muscles) during the period of vibration exposure. Although little is known about the nature and duration of whole-body vibration as it occurs in flight, the results of this part of the study give encouragement that the provision of aircrew with a suitable protective supporting garment might eliminate or reduce the flight hazards associated with the onset of hyperventilation and hypocapnia during conditions of prolonged and severe vibration in flight. It is clear, however, that considerably more work in this field is essential.

In the second part of the experimental studies, reported in Chapter 6 of this thesis, subjects were exposed to whole-body vibration at a constant acceleration amplitude ($\pm$ 0.4 Gz) and at frequencies from 2 - 10 Hz. These studies confirmed the findings reported by Dixon et al (1961), Ernsting (1961) and Duffner et al (1962), that whole-body vibration at a constant acceleration amplitude and at certain frequencies causes an increase in pulmonary ventilation in the experimental subject. Unlike the respiratory changes observed during whole-body vibration at a constant displacement amplitude, the greatest increase in pulmonary ventilation occurred at the lower range of frequencies studied and the maximum changes occurred with a forcing frequency of 6 Hz. Analysis of the data from this series of experiments showed that the relative increase in pulmonary ventilation obtained with exposure to vibration at a frequency of 6 Hz was of the same order of magnitude as the corresponding relative increase in metabolic oxygen uptake, and the increase in pulmonary ventilation was not, therefore, hyperventilation. This belief was supported by the measurements of end tidal carbon dioxide tension and respiratory exchange ratio obtained during the period of vibration exposure. On the other hand it was shown that the increase in pulmonary ventilation which occurred with exposure of the subject to vibration at the lower frequencies of 2 Hz and 4 Hz was greater than the corresponding increase in metabolic oxygen uptake, and this suggested that a true hyperventilation occurred at these frequencies. This was further reinforced by the observation that there was a greater increase in carbon dioxide output than in oxygen uptake as reflected by the values of respiratory exchange ratio. Also, determination of end tidal carbon dioxide tension obtained during vibration of the subject at these frequencies showed that there was a moderate hypocapnia (end tidal carbon dioxide fell by 5.3 mm Hg at a frequency of 2 Hz). In contrast, however, to the results obtained in the constant amplitude vibration studies, no subject reported symptoms which could be referred to those of hypocapnia.

Considerable interest attaches to the finding of hyperventilation and hypocapnia with exposure of the subject to vibration at constant acceleration-amplitude. At these frequencies of vibration (2 Hz and 4 Hz) where this phenomenon occurred, there were no symptoms of discomfort or pain reported by the experimental subjects. In the discussion which followed this part of the experimental investigations arguments were put forward in favour of the belief that the mechanism causing hyperventilation and hypocapnia in the subject exposed to vibration at constant acceleration was different from that causing the phenomenon during exposure of the subject to vibration at a constant amplitude of displacement. It was suggested that the explanations for the hyperventilation associated with vibration exposure of this type might be related to labyrinthine stimulation due to vertical and rotational head movements. This explanation was also suggested by Dixon et al (1961) and Ernsting (1961), who found considerable hyperventilation in subjects exposed to whole-body vibration at constant acceleration and low frequencies.

In the investigations carried out by Dixon et al (1961) and Ernsting (1961) the magnitude of the increase in pulmonary ventilation induced by whole-body vibration at a constant acceleration-amplitude and certain frequencies was considerably greater than that obtained in the present series of experiments, using conditions of vibration exposure similar to those used by the previous authors. This observation suggested that the differences in the magnitude of the respiratory changes induced by whole-body vibration in the two previous and two present experiments might be explained on the basis of posture adopted by the experimental subjects during the period of vibration. It was believed that the adoption of a semi-reclining posture (similar to that used by aircrew) might cause a distribution of the forces of vibration away from the spinal axis in such a way as to protect the head from violent vertical and rotational movements. In this way it was thought possible that stimulation of the labyrinth might also be reduced during the period of vibration and that this in turn might reduce the magnitude of the respiratory changes induced by whole-body vibration at a constant acceleration amplitude and at the lower frequencies studied.

In the experiments reported in Chapter 7 of this thesis, the experimental subject was exposed to vibration at a constant acceleration-amplitude whilst seated on the vibrator first in an upright posture and then in a semi-reclining posture. The results of that study showed that irrespective of the posture adopted by the subject, vibration at frequencies of 2 Hz and 4 Hz caused an increase in pulmonary ventilation which was a true hyperventilation with hypocapnia. With both postures, the magnitude of the hyperventilation and the resulting hypocapnia was the same, although the absolute values for pulmonary ventilation and metabolic oxygen consumption were higher in the condition of the experiment where the subject adopted an upright rather than a semi-reclining posture. The differences in the values of these respiratory variables probably reflected the increased muscular effort required by the subject to maintain his posture in the upright state. An additional experiment was carried out to study the effects of an upright and a semi-reclining posture on the head movements exhibited by the subject during exposure to whole-body vibration at an acceleration amplitude of $\pm$ 0.1 Gz and at frequencies of 2, 4 and 6 Hz. The results of that study showed that for the conditions of vibration used, the adoption of either an upright or a semi-reclining posture had no effect upon the magnitude of vertical or rotational components of head movement recorded during the period of vibration. Arguments were put forward for believing that the same would hold true for conditions of vibration at a higher intensity (acceleration-amplitude = $\pm$ 0.4 Gz) of the type used in the main experiments in this investigation. From a practical point of view, the results have suggested that a semi-reclining posture of the type used by most aircrew sitting in an aircraft seat, would not protect the subject exposed to certain conditions of whole-body vibration in flight from the respiratory disturbances induced thereby (e.g. hyperventilation and resulting hypocapnia), although a certain measure of protection might be afforded by the adoption of this sitting posture from the increased metabolic activity which would be required to maintain an upright posture.

The practical significance of the findings in the present study relate to possibility that hyperventilation and hypocapnia may be induced in aircrew by certain types of vibration occurring in flight. Although the nature and duration of in-flight vibration has not yet been clearly defined for various types of aircraft, it is known that random structure-borne vibration can occur over quite long periods in aircraft operating at high speed and low level, particularly in conditions of turbulence. Although the nature of the vibration is random, there is evidence that the fundamental frequency of this type of oscillatory disturbance lies in the frequency range 1 - 10 Hz and may be responsible for the production of respiratory changes similar to those observed during the experimental vibration used in the present investigations. The danger of hyperventilation and hypocapnia during flight in conditions of whole-body vibration lies in its effects upon the performance of aircrew in flight and in its possible synergism with other forms of environmental stress in aviation. It is, therefore, necessary to examine the significance of hyperventilation in the aviation situation in order to appreciate the importance of this finding in conditions of whole-body structure-borne vibration.

In aviation, hyperventilation may be either a physiological reaction to hypoxia or a stress reaction. Except in serious emergency situations, hypoxia is not likely to be of sufficient magnitude as to cause aircrew to hyperventilate but as a reaction to a stressful situation, hyperventilation may be common and at times responsible for marked changes in psychomotor performance. Although hyperventilation in flight may have been recognised before this time, Hinshaw and Boothby (1941) drew attention to the possible hazards of this condition when they reported that one of the authors had experienced symptoms of tetany when attempting to land an aircraft in adverse weather conditions. He was able to repress his urge to hyperventilate, his symptoms disappeared and he landed his aircraft safely. Since that time other reports have been published (Hinshaw, Rushmer and Boothby, 1943; Rushmer and Bond, 1944), and many other in-flight incidents which suggest the occurrence of hyperventilation, have been recounted to medical officers associated with flying personnel. It has been difficult to assess the significance of these reports because many factors may be involved in the causation of bizarre in-flight conditions. One of the great difficulties lies in distinguishing between the effects of hyperventilation and hypoxia (Wayne, 1957), and a decision as to whether either or both of these conditions has been responsible for an in-flight incident involving disturbance of consciousness is usually extremely difficult to make from retrospective questioning and clinical examination of the affected crew member. There is, therefore, very little known about the true nature of and causative factors involved in this condition and because of the potential hazard which in-flight hyperventilation presents, work is still in progress attempting to assess the significance of this condition in aviation.

From the knowledge which is currently available it would appear that the main hazard associated with the onset of hyperventilation and hypocapnia in aircrew during flight lies in the adverse effect which this condition has on the performance of complex tasks. It is not known with any degree of certainty to what extent hyperventilation affects such performance although Rahn, Otis, Hodge, Epstein, Hunter and Fenn (1946) concluded that there was little decrement in the performance of a psychomotor task until the alveolar carbon dioxide tension had fallen to about 25 mm Hg. It is disturbing to note that in the present investigation three of the experimental subjects developed quite marked symptoms of hyperventilation with hypocapnia after three minutes exposure to vibration at a constant amplitude of displacement and at the higher frequencies in the range studied. In these subjects the symptoms presented as tingling of the hands and feet with quite marked feelings of 'mental detachment'

which persisted unchanged throughout the period of vibration. In the subjects showing symptoms of hypocapnia, the end-tidal carbon dioxide tensions fell from values of 38 - 40 mm Hg obtained during the period of rest prior to vibration, to values of 28 - 32 mm Hg obtained during the period of vibration. It is quite clear that if such a degree of hyperventilation and hypocapnia was to occur during flight as a result of in-flight structure-borne vibration, the resulting deterioration in the mental condition of the subject could be serious.

While laboratory studies on the effects of hypocapnia have shown that deterioration in the performance of a mental task may not become apparent until the alveolar carbon dioxide tension has fallen to about 25 mm Hg, it should be borne in mind that in aviation, symptoms of hyperventilation and hypocapnia could arise in aircrew already affected by other stresses of flight. Thus, it has been stated that structure borne whole-body vibration is liable to occur in the type of flight in which the pilot is required to operate at very high speeds and low level where conditions of severe meteorological turbulence may prevail. In these circumstances, high speed flight through high density air brings with it the disturbance of heat stress to the occupant of the aircraft and the resulting deterioration in mental performance which this is known to cause. In addition, flight of this type necessitates a considerable work load on the part of the pilot who is required to fly his aircraft for strategic purposes very close to the ground with the constant danger of ground contact. It has been shown (Norris, 1964) that the phases of flight in an aircraft which demand intensive concentration on the part of the pilot (e.g. instrument flying in poor visibility, or terrain following flight) are those which may induce an increase in pulmonary ventilation, hyperventilation and hypocapnia in aircrew. It is believed that in the already stressful conditions of low-level, high-speed flight in a modern high performance aircraft the addition of even a mild degree of hyperventilation and hypocapnia induced in the pilot, could represent a serious hazard.

PART II

Metabolic oxygen consumption

The measurements of gaseous exchange which were made during the constant amplitude series of experiments have shown that when the force of vibration applied to the subject was high, there was an increase in the metabolic oxygen uptake. Thus, when the subject was exposed to whole-body vibration at a constant amplitude of displacement and at frequencies of 6, 8 and 10 Hz, the increase in mean values of metabolic oxygen consumption, over values obtained at rest, were 25%, 50% and 72% respectively. In each case, the increase in metabolic oxygen consumption occurred within the first few minutes after the start of vibration, reached a maximum value after five minutes of exposure to vibration and thereafter was sustained, almost unchanged throughout the entire period of vibration. At the termination of vibration and during the subsequent period of recovery, the mean values of metabolic oxygen consumption fell to below those obtained in the period of rest prior to vibration. These findings confirm the early observations by German workers that severe whole-body vibration may induce manifestations of alarm in the experimental subject with, among other changes, an increase in metabolic activity. They also confirm and extend the findings of Ernsting (1961) and Gaeuman et al (1962) that whole-body vibration at high intensities causes a marked increase in metabolic activity in the seated experimental subject. In Ernsting's investigations, however, a significant increase in metabolic oxygen uptake was recorded only at a forcing frequency of vibration of 9.5 Hz and at an acceleration-amplitude of $\pm$ 0.5 Gz, whereas, in the experiments carried out by Gaeuman and his co-workers, a linear increase in oxygen consumption was reported with increasing frequencies from 6 to 15 Hz at a fixed displacement-amplitude of $\pm$ 0.132 in. These latter workers used conditions of whole-body vibration, which were similar to those used in the present series of experiments and the results obtained in the two investigations are also similar.

In these two main previous studies carried out on the metabolic activity of the subject exposed to whole-body vibration, the authors believed that the marked increase in the respiratory variable was due to the increased muscular effort required by the experimental subject to maintain his posture in the face of violent shaking in the vibrator seat. It will be recalled that in both these studies, the subject sat either directly on the platen of the vibrator or in a simple upright seat during the period of vibration exposure. In neither case was the subject restrained by any form of harness restraint system and the authors noted that considerable effort was required by the subject to remain seated in the upright position during the entire period of vibration exposure. In the present series of experiments, the validity of this explanation for the increase in metabolic activity during vibration was tested by exposing subjects to constant amplitude vibration whilst seated in an aircraft type seat either restrained or unrestrained by a well tested harness system of known efficacy. The results of this part of the study indicated that an increase in metabolic oxygen consumption occurred in the experimental subject during exposure to vibration at high intensities, and that this occurred with the same magnitude irrespective of whether the subject was restrained or unrestrained in the vibrating seat. In the experiments in which the torso of the subject was fully restrained by harness, no effort was required on his part to maintain posture during the period of vibration exposure, and it was considered that maintenance of posture could not be the primary cause of the increased metabolic activity which was observed.

In an earlier investigation Cörmann (1940) noted that almost immediately upon exposing his subjects to whole-body vibration at certain frequencies and intensities there was an obvious generalised increase in the tension of various groups of muscles throughout the body. From a study of this early report, it appeared that the muscle masses involved in this phenomenon were not those normally associated with maintenance of posture and this suggested the possibility that tensing of musculature as a result of some mechanism other than that related to posture might explain the increase in metabolic activity during whole-body vibration exposure. In the present series of experiments, therefore, the behaviour of various groups of muscles was examined during different conditions of exposure to vibrations using a technique of high speed cinematography. A frame by frame analysis of the exposed cine film revealed that during exposure of the subject to whole-body vibration at a constant displacement amplitude and at frequencies of 6, 8 and 10 Hz, various groups of muscles visible on the surface of the body exhibited alternate periods of tensing and relaxation throughout vibration exposure. At the higher intensities of vibration studied (8 Hz and 10 Hz) a number of muscle groups exhibited a sustained contraction throughout vibration while others showed long periods of contraction and short periods of relaxation. It was also noticed that the muscle groups which exhibited this phenomenon during vibration were not necessarily those associated with maintenance of posture. It was believed that this phenomenon was the most likely explanation for the increased metabolic oxygen consumption observed during exposure of the subject to high intensity whole-body vibration. While it must remain speculation, it was considered possible that the muscular activity observed during vibration could be partly voluntary and partly involuntary as an attempt by the body to alter its mechanical impedance characteristics, modify or redistribute the transmission of the input vibration or alter resonance characteristics in such a way as to protect certain more vulnerable parts from the effects of the vibration disturbance. In support of this view it was found that when the subject exposed to high intensity vibration was asked to attempt deliberate relaxation of his muscles he could do so for only a brief period and during that time differential movement of various parts of the body was noticeably increased to an extent which caused him very severe discomfort or frank pain.

In contrast to the results obtained in the constant amplitude vibration studies, it was shown that on exposure of the experimental subject to whole-body vibration at a constant acceleration ($\pm$ 0.4 Gz) there was a relatively minor increase in metabolic oxygen consumption at frequencies of 2 Hz and 4 Hz, a fairly marked increase at a frequency of 6 Hz and no appreciable change in metabolic activity at frequencies of 8 and 10 Hz. The increase in metabolic oxygen consumption observed in the subject exposed to vibration at a constant acceleration ($\pm$ 0.46 Gz) and at a frequency of 6 Hz was similar in magnitude to the increase observed at this frequency during exposure of the subject to vibration at a constant displacement amplitude (acceleration amplitude in that series = $\pm$ 0.5 Gz). It is of interest to note that at this frequency exposure of the subject to vibration at a constant acceleration caused the only symptoms of discomfort recorded during this series of vibration experiments although as previously stated, it was considered that these were of insufficient magnitude to induce symptoms of hyperventilation and hypocapnia in the subject. Although no formal cinematographic studies were carried out on the behaviour of muscle masses during vibration in that series, direct observation of the subject gave clear evidence that on exposure to vibration at 6 Hz and an acceleration amplitude of $\pm$ 0.4 Gz the subject tensed a number of muscle groups either as a voluntary or involuntary procedure. It was believed, therefore, that the increased metabolic activity observed at this frequency of vibration could be explained on the same basis as for that observed at the same frequency in the constant amplitude series.

With exposure of the subject to whole-body vibration at a constant acceleration and frequencies of 2 Hz and 4 Hz there was in each case a small increase in metabolic oxygen consumption. Although small in absolute terms, it was observed that the increase in metabolic activity with exposure of the subject to vibration at these frequencies was significantly greater when he was unrestrained than when he was restrained by harness in the vibrating seat. This finding immediately suggested that the increased metabolic activity obtained at the lower frequencies in the range studied is probably due to the muscular activity required to maintain posture in the face of vibration. It should be noted that in order to maintain a constant amplitude of acceleration ($\pm$ 0.4 Gz) at these lower frequencies, a large displacement amplitude setting was required for the platform of the vibrator. In support of the view that maintenance of posture was the mechanism responsible for the small increase in metabolic activity during exposure to vibration at frequencies of 2 Hz and 4 Hz, is the observation that there was no perceptible muscle tensing in any of the subjects all of whom reported that this condition of vibration was not associated with any appreciable discomfort. In further support of this hypothesis is the finding that when the subject was exposed to vibration at a constant acceleration amplitude and frequencies of 2 Hz and 4 Hz whilst seated in an upright posture without any form of back support, the measured metabolic oxygen consumption was significantly higher than that obtained at the same frequencies with the subject seated in a semi-reclining posture in an aircraft type seat. In these experiments (reported in Chapter 7) it was noted that at the lower frequencies in the range studied (2 Hz and 4 Hz) the subject seated upright in the specially modified seat required continual and considerable effort to maintain his posture.

It is concluded, therefore, that there may be two mechanisms involved in the increased metabolic activity observed in the subject exposed to low frequency whole-body vibration. At certain frequencies of vibration where there is a large amplitude of displacement but where there is no voluntary or involuntary tensing on the part of the exposed subject, muscular activity is required simply to maintain posture during the vibration and this is reflected by a small increase in metabolic oxygen consumption. In other conditions of vibration at higher intensities it appears that there is a generalised reflex tensing of musculature. With these latter conditions of vibration it is most likely that any increase in muscular activity due to the requirements to maintain posture are insignificant.

It has been stated previously that a knowledge of the metabolic oxygen consumption (metabolic heat output) of the subject exposed to all conditions likely to be encountered in operational flight is of practical importance to the maintenance of comfort, well being and safety of aircrew. Thus a knowledge of the metabolic activity in aircrew exposed to conditions of flight in which low frequency whole-body vibration occurs, is of value in the design of aircraft and personal thermal conditioning systems, which are required to maintain the occupant in thermal comfort and enable him to carry out his in-flight tasks efficiently.

In the past, however, it has been very difficult to assess the requirements for aircraft or personal thermal conditioning in various types of flying condition since there is little information available on the metabolic energy expended by the pilot flying different types of aircraft and until now very little information on the effect of structure-borne vibration on metabolic activity in aircrew. In reviewing the literature it was stated that the work of previous authors shows that in terms of energy expenditure and physical activity the total flight profile of any aircraft may be considered as a number of different phases (e.g. ascent to altitude, routine flight, emergency situation, etc.) all of which place differing demands on the pilot. In almost all of these phases of flight, and unfortunately in many of those where the workload of the pilot is already quite considerable, whole body structure borne vibration may be encountered and may significantly add to the problem of maintaining the pilot in a condition in which he can carry out his tasks efficiently.
With these adverse effects of whole body vibration in mind, the final part of this discussion highlights some of the areas where its occurrence could prove embarrassing to aircrew operating under different conditions of flight. This aspect is discussed in terms of the metabolic energy expenditure required by the pilot to fly high performance and helicopter aircraft.

One type of flying in which the occurrence of structure borne whole-body vibration gives rise to the greatest concern is that of high performance aircraft. It is unfortunate that there is very little information regarding the energy expended by the pilot flying aircraft of this type, although there is meagre evidence to suggest that maintenance of normal routine flight in this type of aircraft requires little energy in excess of that required at rest. From a review of the literature, however, there is evidence that the execution of intense aerobatic manoeuvres of the type required for attack or defence in the combat situation requires considerable energy expenditure on the part of the pilot. Thus from a mean value of energy expenditure of 50 kcal/m^2hr obtained with the pilot at rest and during routine straight and level flight, the execution of a combat type aerobatic manoeuvre causes an increase in energy expenditure to a mean value of 80 kcal/m^2hr. This latter value of energy expenditure is mainly due to the physical effort required to operate the control column and rudder pedals during the execution of the manoeuvre. Although there have been no measurements taken of the energy expended by the pilot required to operate an aircraft of this type at high speed and low level it is highly likely that the physical effort required by the pilot to maintain the altitude of the aircraft is greater than that required during an aerobatic manoeuvre at higher altitudes.

Thus it is known that flight at low altitudes and at high speed requires considerable skill and activity on the part of the pilot in order to clear objects on the ground, and flying conditions of this type are well known as a cause of intense fatigue in the pilot. As previously stated, high speed low level flight often requires penetration of turbulent airspace with the added problem of structure borne whole body vibration. In the experiments carried out in this investigation, it was shown that whole body vibration at certain frequencies and intensities may require the expenditure of energy in the order of 80 kcal/m^2hr. In his report, Hughes (1968) showed that energy expenditure of this magnitude requires that the air entering the aircraft cabin must be considerably reduced in temperature in order to maintain the occupant in thermal comfort. In conditions of high speed low level flight there may be other factors present which place a heavy demand in the aircraft conditioning system and there is a risk that the occupants may be exposed to thermal stress. It is known that heat stress in aircrew affects the ability to perform psychomotor tasks and this condition could be an in-flight hazard particularly in conditions of flight demanding a high degree of mental skill and flying ability. In addition, the increased muscular activity induced by whole-body low frequency vibration must add in some measure to the fatigue experienced by the pilot required to fly a high performance aircraft in these conditions.

Finally, the increased metabolic activity in aircrew exposed to low frequency structure borne vibration must be examined in relation to helicopter flying. It has been stated previously that severe vibrations may be generated in the engines, gearboxes and rotor blades in this type of vehicle, and these may be transmitted through the structure of the aircraft to the seated occupant. The importance of whole body vibrations which may arise during flight in a helicopter lies in the fact that even under normal conditions this type of flying demands some of the greatest expenditure of energy on the part of the pilot, as well as constant vigilance and mental concentration. Any factors which might reduce the ability of the pilot to carry out his in-flight task with efficiency or which impose additional workload during periods of critical flight, are of particular concern in aircraft of this type. Thus it has been shown that the greatest expenditure of energy by pilots flying helicopters occurs during in-flight phases close to the ground (e.g. hovering, ascent and descent). This is in contrast to the relatively small amount of energy required to fly helicopters at higher altitudes. It is likely that manoeuvres close to the ground demand from the pilot more precise and active operation of the aircraft controls than is required with flight at a significant altitude. The mean energy expended by helicopter aircrew (mean value = 70, range 55 - 97 kcal/m^2hr) during operation of the aircraft close to the ground is similar in value to that expended by aircrew flying conventional fixed wing aircraft in an emergency situation (e.g. with all control servo-systems inoperative). It is, however, worthy of consideration that while the high values of energy expenditure by aircrew flying fixed wing aircraft occur during an infrequent emergency situation, high levels of physical activity and energy expended by helicopter aircrew occur as a routine part of the normal operational flight profile. It should also be remembered that structure borne vibration is constantly present during helicopter flight and unlike the situation in fixed wing aircraft is not simply an occurrence associated with infrequent phases of flight.

In conclusion, it is now clear that aviation, and particularly military aviation, can occasion some of the worst conditions of vibration to which man may be exposed. The investigations reported in this thesis have drawn attention to two important human responses to whole-body vibration which may threaten the safety and comfort of aircrew required to operate in certain conditions of flight. Thus it has been shown that at certain amplitudes and frequencies, whole-body vibration may induce an increase in pulmonary ventilation which is a true hyperventilation, and in some instances this may be accompanied by quite marked symptoms of hypocapnia. It has been stated that the occurrence of such symptoms may seriously impair the ability of the pilot to perform his task efficiently and may, therefore, represent a flight hazard. The investigation has also shown that whole-body vibration at certain frequencies and amplitudes may cause a marked increase in metabolic energy expenditure in the subject. While this latter respiratory change may not represent the serious in-flight hazard associated with hyperventilation and hypocapnia it may, nonetheless, interfere with the comfort and wellbeing of aircrew required to operate in conditions of in-flight vibration. In addition the increased muscular activity induced in the subject by certain conditions of vibration may contribute to the fatigue experienced by aircrew in their flight mission.

One of the prime objectives in the practice of aviation medicine is to define the nature of the disturbance affecting aircrew, to investigate the factors which influence that disturbance and finally to design possible methods of overcoming or reducing the disturbance. In the present studies the respiratory effects of whole-body vibration have been defined and a number of factors affecting the respiratory responses (e.g. harness restraint, sitting posture and thoraco-abdominal support) have been investigated. These investigations have suggested other lines of study which it is hoped may eventually lead to the final solution - that of eliminating the disturbance to aircrew. The path to this final solution is long and difficult and much work is currently being undertaken in the field of vibration control to devise methods of reducing or eliminating the disturbance at source, reducing the vibration in its route of transmission to man or in attenuating the effects of vibration in the man himself. Many of these approaches to the problem involve engineering skills and final success will require close co-operation between physician, physiologist and engineer. It is hoped that the work described in this thesis may have helped towards achieving success in this field. It is also hoped that the investigations may have contributed in some measure to the aims of aviation medical practice - the promotion of safety, comfort and wellbeing in all types of flight.

General Conclusions

The respiratory effects of vertical sinusoidal vibration applied to the buttocks of a seated subject have been investigated over the frequency range 2 - 10 Hz at acceleration amplitudes of up to $\pm$ 1.4 Gz. The following main findings and conclusions have been reached.

1. Whole body vibration at certain frequencies and accelerations caused a significant increase in pulmonary ventilation. This was brought about by increases in both respiratory frequency and tidal volume. When the amplitude of displacement of vibration was held constant, there was a greater increase in pulmonary ventilation at the higher frequencies than at the lower ones investigated, whilst when the peak acceleration of the applied vibration was held constant the reverse held true. This phenomenon was, therefore, neither solely acceleration nor amplitude dependent.

2. At certain frequencies and amplitudes whole body vibration induced marked hyperventilation in the experimental subject. Evidence for this respiratory change was adduced from the finding of a relative increase in pulmonary ventilation which was greater than the corresponding increase in metabolic oxygen consumption at these frequencies of vibration. Also, there was a greater increase in carbon dioxide output than in oxygen uptake (as reflected by values of respiratory

exchange ratio) and there was a reduction of pulmonary ventilation and respiratory exchange ratio in the recovery period below their respective control values. With constant amplitude vibration, hyperventilation occurred at the higher frequencies studied (6, 8 and 10 Hz) whilst with constant acceleration vibration it occurred at the lower frequencies studied (2 Hz and 4 Hz).

3. Under all the conditions of vibration exposure in which hyperventilation was induced in the subject there was also a moderate to severe hypocapnia. Marked symptoms of hypocapnia were obtained in some subjects during exposure to constant amplitude vibration at high frequency and intensity (8 Hz). With constant amplitude vibration severe hypocapnia was induced at the higher frequencies studied (6, 8 and 10 Hz) whilst with constant acceleration vibration a moderate to severe hypocapnia was induced at the lower frequencies (2 Hz and 4 Hz). With this latter type of vibration the magnitude of the hypocapnia was not sufficient to give rise to symptoms in the experimental subject.

4. With constant amplitude vibration at high frequencies, the respiratory changes were accompanied by severe pain in the thorax and abdomen of the subject. The degree of discomfort increased with increasing intensity of vibration. It was concluded that discomfort was the most likely cause

of the hyperventilation and hypocapnia during constant amplitude vibration exposure. With constant acceleration vibration no such discomfort or pain accompanied the observed respiratory changes and it was tentatively suggested that labyrinthine stimulation might have been the causative factor in the production of hyperventilation and hypocapnia.

5. Sound restraint of the subject in the vibrating seat (by means of an aircraft torso harness system) failed to eliminate or reduce the respiratory changes observed during exposure to whole-body vibration of both types (constant amplitude and constant acceleration).

6. When external support was applied to the thorax and abdomen of the vibrated subject (by means of a restrainer suit) the respiratory changes induced by constant amplitude whole-body vibration were either eliminated or greatly reduced. It was concluded that thoraco-abdominal support helped to prevent painful resonance movement of viscera and pectoral muscles during vibration and that this in turn prevented or reduced the onset of hyperventilation and hypocapnia.

7. With exposure to constant acceleration vibration, the posture adopted by the subject in the vibrating seat (either semi-reclining or upright) did not influence the respiratory changes induced at certain frequencies and amplitudes. The magnitude of the vertical and rotational components of

acceleration at the head were the same for both postures during each condition of vibration, and it was concluded that stimulation of the labyrinth during vibration was similarly unaffected by posture.

8. The magnitude of the hyperventilation and hypocapnia induced by experimental whole body vibration at certain frequencies was sufficient to give rise to concern for the safety and wellbeing of aircrew exposed to similar conditions of vibration in flight. It was concluded that if these respiratory changes were to arise in aircrew during conditions of low level, high speed flight the resulting deterioration in mental condition could be hazardous.

9. Whole body vibration at a constant displacement amplitude caused a marked increase in metabolic oxygen consumption at the higher frequencies studied (6, 8 and 10 Hz).

10. The increase in oxygen consumption was not caused by the increased muscular effort required by the subject to maintain his posture during violent shaking. Values of metabolic oxygen consumption obtained with the vibrated subject were similar in magnitude for the conditions in which he was restrained and unrestrained by harness in the vibrating seat.

11. From examination of high speed cinephotographs taken during exposure of the subject to constant amplitude vibration it

was observed that alternate tensing and relaxation of various groups of muscles occurred during high intensity vibration. It was concluded that this muscular activity was probably protective in nature and was responsible for the increased metabolic activity during certain conditions of vibration.

12. During exposure of the subject to vibration at a constant acceleration there was a moderate increase in metabolic oxygen consumption at the lower frequencies studied (2 Hz and 4 Hz) and a larger increase at a frequency of 6 Hz. No increase in oxygen consumption was obtained with vibration at frequencies of 8 Hz and 10 Hz. It was concluded that the metabolic activity at a frequency of 6 Hz was due to muscular tensing (similar in nature to that observed with constant amplitude vibration at that frequency). At frequencies of 2 Hz and 4 Hz, no muscular activity was observed during vibration and it was concluded that the increased oxygen consumption was due to requirements for the subject to maintain his posture during vibration.

13. Values of energy expended by the subject during exposure to whole body vibration at certain frequencies and amplitudes were similar in magnitude to those obtained in aircrew flying helicopters and high performance aircraft in demanding roles (e.g. emergency and combat situations, instrument flying and aerobatic manoeuvres). It was concluded that whole body

structure borne vibration occurring in flight would represent a threat to thermal comfort in aircrew and would in certain types of flying situations contribute to in-flight fatigue.

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FORM OF APPLICATION FOR DEGREE OF M.D.

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DECLARATION I declare that the work has been done and the thesis composed by myself, and that the books and papers cited were all consulted by me personally, unless it is otherwise stated.

(NOTE: where material based on work undertaken in collaboration with others is included in the thesis a further and separate statement must be submitted clearly defining the candidate's individual contribution)

DATE: 14/2/1972 SIGNED: Gordon R Sharp

CERTIFICATION:

I hereby certify that the above named candidate for the degree of M.D. has been engaged since graduation for at least one year either in scientific work bearing directly on his profession or in the practice of Medicine.

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THE RESPIRATORY EFFECTS

OF WHOLE BODY VIBRATION IN MAN

Separate summary of a thesis
submitted in candidature
for the degree of Doctor of Medicine

by

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THE RESPIRATORY EFFECTS OF WHOLE BODY VIBRATION IN MAN

A Separate Summary

In the field of aviation medicine, there is considerable interest in the physiological effects of low-frequency, structure borne vibration in man. This has been brought about by the requirement for certain military aircraft to operate at high speed and low level in conditions of meteorological turbulence. In-flight conditions of this type may induce short duration accelerations in the aircraft, which resemble mechanical noise with superimposed quasi-steady state vibrations due to air-frame structural responses. To those who practise aviation medicine, vibrations produced in aircraft flying in these conditions are of particular interest since they present at frequencies below about 15 Hz, at which, both human body resonances amd major aircraft modes are excited into large amplitude oscillations. The presence of structure-borne vibrations of this type becomes of concern when they reach such intensity as to disturb normal flight in the aircraft, and in particular, where they represent a threat to comfort, health or efficiency in aircrew flying the aircraft.

A review of the literature has shown that there have been comparatively few studies on the physiological disturbances

brought about by structure borne whole body vibration in the low frequency range, although it is known that they may affect man in a variety of different ways. A number of these disturbances may occur singly or may be compounded with other stresses liable to be encountered during certain types of flight (for example, long duration acceleration, noise, heat and high work load). There is, however, a paucity of information concerning the respiratory effects of whole body vibration in man and the investigations, which are described in this thesis, were designed in order to advance knowledge in this field and to provide information which can be used to improve the comfort safety and well-being of aircrew operating in conditions of in-flight vibration. In particular, two areas of disturbance have been investigated - that relating to the effects of vibration on pulmonary ventilation and gaseous exchange in man, and that relating to the metabolic energy expended by man during low frequency whole-body vibration.

The investigation was carried out using a mechanical vibration generator which applied sinusoidal vibrations in the low frequency range to the buttocks of a subject seated in a modified aircraft ejection seat. The respiratory effects of vertical sinusoidal vibration were investigated over the frequency range 2 - 10 Hz at acceleration amplitudes of up to $\pm$ 1.45 Gz. Using various conditions of experimental vibration, measurements were made of pulmonary ventilation, end-tidal carbon dioxide tension and gaseous exchange during a period of rest, during exposure of the subject to the chosen conditions of vibration and during a subsequent recovery period following the vibration. Measurements were also made of oxygen consumption and carbon dioxide output using an 'open circuit' technique during each phase of the experiment. These respiratory variables were studied during exposure of the subject to whole body vibration in which the relationship between the displacement amplitude and vibration frequency varied in two ways. In one series of experiments the total amplitude of vibration was held constant at 0.625 cm over the frequency range 2 - 10 Hz which was explored in frequency steps of 2 Hz (constant amplitude vibration). In the other series, the displacement amplitude was adjusted to maintain an acceleration of vibration at $\pm$ 0.4 Gz over the same frequency range (constant acceleration vibration). In this way, the respiratory effects of whole body vibration were studied over a wide range of frequencies and acceleration amplitudes.

In order to investigate the causative mechanisms involved and the factors affecting the respiratory changes induced in man by whole body vibration, additional experiments were carried out in the main programme. In some of the experiments, the respiratory effects of vibration were studied with the subject fully restrained in the vibrating seat by means of a typical modern aircraft torso harness restraint system and the results were compared with those obtained with the subject unrestrained by harness in the seat. In another study, the influence of thoraco-abdominal restraint on the respiratory effects of whole-body vibration was investigated using a standard item of aircrew personal equipment, and the results were compared with those obtained when the subject was vibrated without thoraco-abdominal support. In one part of the investigation a study was made of the effects of sitting posture (either upright or semi-reclining posture) on the respiratory changes induced by whole body vibration and in order to throw light on the possible causative mechanisms involved in these changes, the vertical and rotational components of head movement during vibration in each sitting posture were also measured. In order to investigate the observed increase in metabolic activity during exposure of the subject to whole-body vibration investigation was also made of the behaviour of various groups of muscles during the period of vibration using a technique of high speed cinephotography.

The main findings and conclusions obtained in this study may be summarised as follows:

1. Whole body vibration at certain frequencies and accelerations caused a significant increase in pulmonary ventilation. This was brought about by increases in both respiratory frequency and tidal volume. When the amplitude of displacement of vibration was held constant, there was a greater increase in pulmonary ventilation at the higher frequencies

than at the lower ones investigated, whilst when the peak acceleration of the applied vibration was held constant the reverse held true. This phenomenon was, therefore, neigher solely acceleration nor amplitude dependent.

2. At certain frequencies and amplitudes whole body vibration induced marked hyperventilation in the experimental subject. Evidence for this respiratory change was adduced from the finding of a relative increase in pulmonary ventilation which was greater than the corresponding increase in metabolic oxygen consumption at these frequencies of vibration. Also, there was a greater increase in carbon dioxide output than in oxygen uptake (as reflected by values of respiratory exchange ratio) and there was a reduction of pulmonary ventilation and respiratory exchange ratio in the recovery period below their respective control values. With constant amplitude vibration, hyperventilation occurred at the higher frequencies studied (6, 8 and 10 Hz) whilst with constant acceleration vibration it occurred at the lower frequencies studied (2 Hz and 4 Hz).

3. Under all the conditions of vibration exposure in which hyperventilation was induced in the subject there was also a moderate to severe hypocapnia. Marked symptoms of hypocapnia were obtained in some subjects during exposure to constant amplitude vibration at high frequency and intensity

(8 Hz). With constant amplitude vibration severe hypocapnia was induced at the higher frequencies studied (6, 8 and 10 Hz) whilst with constant acceleration vibration a moderate to severe hypocapnia was induced at the lower frequencies (2 Hz and 4 Hz). With this latter type of vibration the magnitude of the hypocapnia was not sufficient, however, to give rise to symptoms in the experimental subject.

4. With constant amplitude vibration at high frequencies, the respiratory changes were accompanied by severe pain in the thorax and abdomen of the subject. The degree of discomfort increased with increasing intensity of vibration, and it was concluded that discomfort was the most likely cause of the hyperventilation and hypocapnia during constant amplitude vibration exposure. With constant acceleration vibration no such discomfort or pain accompanied the observed respiratory changes and it was tentatively suggested that with vibration of this type, labyrinthine stimulation might have been the causative factor in the production of hyperventilation and hypocapnia.

5. Sound restraint of the subject in the vibrating seat (by means of an aircraft torso harness system) failed to eliminate or reduce the respiratory changes observed during exposure to whole-body vibration of both types (constant amplitude and constant acceleration). On the other hand, when external support was applied to the thorax and abdomen of the vibrated

subject (by means of a restrainer suit) the respiratory changes induced by constant amplitude whole-body vibration were either eliminated or greatly reduced. It was concluded therefore that thoraco-abdominal support helped to prevent painful resonance movement of viscera and pectoral muscles during vibration and that this in turn prevented or reduced the onset of hyperventilation and hypocapnia.

6. With exposure to constant acceleration vibration, the posture adopted by the subject in the vibrating seat (either semi-reclining or upright) did not influence the respiratory changes induced at certain frequencies and amplitudes. The magnitude of the vertical and rotational components of acceleration at the head were the same for both postures during each condition of vibration, and it was concluded that stimulation of the labyrinth during vibration was similarly unaffected by posture.

7. The magnitude of the hyperventilation and hypocapnia induced by experimental whole body vibration at certain frequencies was sufficient to give rise to concern for the safety and wellbeing of aircrew exposed to similar conditions of vibration in flight. It was concluded that if these respiratory changes were to arise in aircrew during conditions of low level, high speed flight the resulting deterioration in mental condition could be hazardous.

8. Whole body vibration at a constant displacement amplitude caused a marked increase in metabolic oxygen consumption at the higher frequencies studied (6, 8 and 10 Hz). This increase in oxygen consumption was not caused by the increased muscular effort required by the subject to maintain his posture during violent shaking, since the values of metabolic oxygen consumption obtained with the vibrated subject were similar in magnitude for the conditions in which he was restrained and unrestrained by harness in the vibrating seat.

9. From examination of high speed cinephotographs taken during exposure of the subject to constant amplitude vibration it was observed that alternate tensing and relaxation of various groups of muscles occurred during high intensity vibration. It was concluded that this muscular activity was probably protective in nature and was responsible for the increased metabolic activity during certain conditions of vibration.

10. During exposure of the subject to vibration at a constant acceleration there was a moderate increase in metabolic oxygen consumption at the lower frequencies studied (2 Hz and 4 Hz) and a larger increase at a frequency of 6 Hz. No increase in oxygen consumption was obtained with vibration at frequencies of 8 Hz and 10 Hz. It was concluded that the metabolic activity at a frequency of 6 Hz was due to muscular tensing (similar in nature to that observed with constant amplitude vibration at that frequency). At frequencies of

2 Hz and 4 Hz, no muscular activity was observed during vibration and it was concluded that the increased oxygen consumption observed at these frequencies was due to requirements for the subject to maintain his posture during vibration.

11. Values of energy expended by the subject during exposure to whole body vibration at certain frequencies and amplitudes were similar in magnitude to those obtained in aircrew flying helicopters and high performance aircraft in demanding roles (e.g. emergency and combat situations, instrument flying and aerobatic manoeuvres). It was concluded that whole body structure borne vibration occurring in flight would represent a threat to thermal comfort in aircrew and would in certain types of flying situations contribute to in-flight fatigue.

Finally, the results of the overall investigations have allowed definition of the major respiratory changes induced by low-frequency whole body vibration. They have enabled a number of causative mechanisms involved in the production of hyperventilation and hypocapnia during vibration, to be advanced and have highlighted the possible dangers of this condition to aircrew operating in high speed low level flight. They have also suggested future lines of investigation which may help to prevent this occurrence in aviation. The results have also shown that whole body vibration may induce high rates of metabolic oxygen consumption in the exposed subject. Possible mechanisms for this increase in metabolic activity have been put forward and the importance of the findings in relation to aviation have been discussed.