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PHYSIOLOGICAL AND MECHANICAL RESPONSE OF THE HUMAN
TO LONGITUDINAL WHOLE-BODY VIBRATION
AS DETERMINED BY SUBJECTIVE RESPONSE

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Biomedical Laboratory
6570th Aerospace Medical Research Laboratories
Aerospace Medical Division
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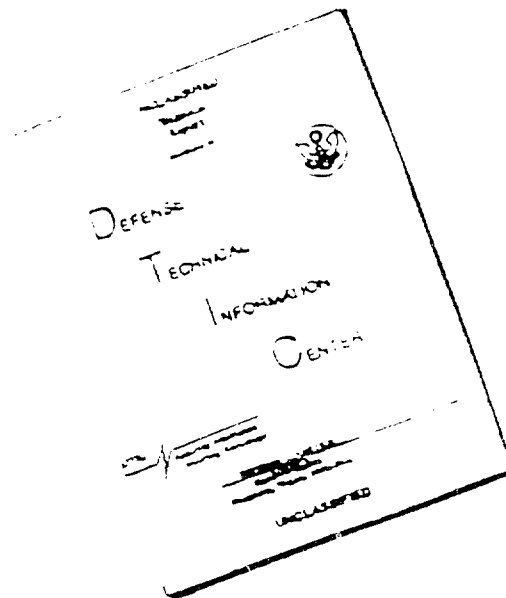
Project No. 7231; Task No. 723101

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FOREWORD

This investigation was conducted during 1959 and 1960 by the Vibration and Impact Section, Bioacoustics Branch, Biomedical Laboratory, under Project No. 7231, "Biomechanics of Aerospace Operations," Task No. 723101, "Effects of Vibration and Impact."

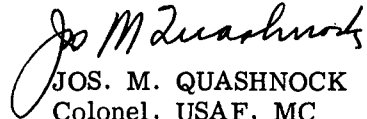
The authors express their appreciation to the voluntary subjects who underwent repeatedly severe vibrational stresses.

ABSTRACT

The production of symptoms in specific body regions to whole-body vibrations is dependent upon physiological alterations resulting from the mechanical stimulation of various organ-tissue complexes of the body. We investigated subjective response to gain an insight into the mechanical properties of the body. Fifteen subjects experienced with whole-body vibrations were included in a two-phase study in an attempt to measure qualitatively and quantitatively subjective response to longitudinal vibrations from 1 to 20 cps in a sitting position. In the first phase the complexity of body response to whole-body vibration was demonstrated since the subjects usually experienced several symptoms for each frequency tested. The second phase suggested that the sensations were resonance-dependent. Mechanical and physiological responses were correlated.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.



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INTRODUCTION

Short-time (1- and 3-minute) tolerance levels to mechanical vibrations in the frequency range from 1 to 20 cps have been ascertained for sitting human subjects restrained by a standard Air Force harness (refs. 1, 2, and 3). Subjective response established the criteria for tolerance in these studies. During the short-time studies, seven symptoms were elicited and appeared to be frequency-dependent. These symptoms were expanded upon during the tolerance studies, and a regional symptomatology was compiled which included 15 specifically defined sensations which also appeared to be frequency-dependent.

The human body exposed to vibrations and buffeting of the frequency range under study principally responds mechanically (mechanodynamically) in the same manner as an inorganic system having lumped parameters. Extrinsically applied alternating forces will produce varying relative displacements of organ systems and their supporting structures. This is dependent upon frequency, magnitude, area, and direction of excitation. Further, for a given type of excitation, the magnitude of displacement will be a function of the natural frequency, damping factor of the system, and coupling to the point of excitation. The stimulus to whole-body vibrations, therefore, is not only dependent upon the force of mechanical excitation, but also upon the mechanodynamic properties of specific organ-tissue complexes. A symptom reflects physiological alteration, and, in this case, is brought about by whole-body vibrations.

This study was designed to investigate symptomatology peculiar to whole-body vibrations during defined vibrational excitation to gain an insight into the mechanodynamic properties of the body.

The investigation was conducted in two phases: (a) the first to determine subjective tolerance for each body region to vibration for a specific type of excitation and (b) the second, with more detailed symptoms, to determine which organs are most affected by vibration at a specific frequency.

SUBJECTS

Fifteen healthy male subjects, experienced in riding various mechanical oscillators, took part in this study. Ten subjects were included in the first phase and all 15 in the second phase. Age, weight, and height of each subject are presented in table I.

The subjects were all experienced in riding the frequencies under investigation. They were well briefed in the concept of introspection having given subjective responses to whole-body vibrations during previous investigations. All subjects had previously reached tolerance levels at various frequencies from 1 to 15 cps (ref. 2).

TABLE I

SUBJECT	AGE	WEIGHT	HEIGHT
A	32	195	6' 0"
B	24	136	5' 11"
C	23	200	6' 1"
D	29	150	5' 9"
E	34	200	5' 10"
F	25	143	5' 7"
G	28	210	6' 0"
H	29	145	5' 7"
I	24	168	6' 0"
J	27	197	6' 3"
K*	42	148	5' 6-1/2"
L*	29	130	5' 7"
M*	23	160	5' 10-1/2"
N*	32	199	6' 1-1/2"
O*	28	140	6' 1-1/2"

*These subjects were added in the second phase of the study.

EQUIPMENT

All vibrations in this study were vertical and of a sinusoidal waveform. The 6570th Aerospace Medical Research Laboratories vertical accelerator was used for low frequencies. This device is capable of producing sinusoidal vibrations with a maximum displacement of ± 10 feet double amplitude (D.A.) and an acceleration limitation of ± 3.5 G's up to 7 cps. A mechanical shake table with a maximum double amplitude of 9 inches was used to attain frequencies ranging up to 20 cps.

The seating arrangement was identical to that of previous tolerance studies (refs. 2 and 3). Figure 1 shows a subject sitting on the vibrating platform of the vertical accelerator. This sitting arrangement was the same for both parts of this study. A modified T-33 jet aircraft seat, consisting of reinforced flat plywood without cushions, was mounted to the vibrating platform. With this, the true motion of the vibrating platform was transferred to the subject with a minimum of change. The subject sat with his coccyx pressed firmly against the back of the seat, so that a nearly vertical position was maintained during the run. A standard Air Force lap belt and shoulder harness were tightly fastened so that the subject could not move in either vertical or horizontal

directions. Care was taken to avoid impairing respiratory movements and changing the mechanical characteristics of the abdomen and its contents. The feet were not strapped down and the head was not supported, although a head rest was attached to the seat to safeguard against severe oscillations. The subject wore a standard Air Force crash helmet with an intercommunication system enabling the subject, medical officer, and vertical-accelerator or shake-table operator to have constant audio contact.



Figure 1. Subject on the Vertical Accelerator

PHASE I

Procedure

The frequencies and accelerations studied in this phase are presented in table II. Frequencies from 1 to 10 cps were investigated for 3-minute periods at tolerance levels. The tolerance levels, predetermined during previous investigations (refs. 2 and 3), were chosen to obtain the maximum effect. The frequencies were divided into three series, each on a separate day. Series 1 and 2 included three frequencies and series 3, four frequencies. The frequencies were staggered in an attempt to have a painful run follow a less painful run. The frequencies of each series were run consecutively with an approximate 5-minute rest period between the runs.

TABLE II
APPLIED AMPLITUDES AND ACCELERATIONS AT TOLERANCE
LEVELS FOR THE FREQUENCY RANGE OF 1 TO 10 cps
(PHASE I)

3-Minute Study		
cps	G Vector	Double Amplitude (in.)
1	1.8	35
2	1.6	8
3	1.3	2.4
4	0.8	1.1
5	0.4	0.31
6	0.4	0.22
7	0.4	0.18
8	0.9	0.27
9	1.0	0.24
10	1.2	0.23

The subjects were instructed that the run should last the entire 3 minutes if at all possible. However, they were cautioned to abort the run immediately if they felt that bodily harm was going to occur. For each ride, the frequency was pre-set and then the oscillating platform was started vibrating, its amplitude increasing from zero to the desired acceleration. This took from 15 to 30 seconds. When the acceleration was attained, the monitors began the time check. The subjects were notified when half of the run had been completed.

Previously (ref. 2), a regional symptomatology consisting of 15 clearly defined symptoms was tabulated and is presented in table III. This table represents a symptom complex peculiar to whole-body sinusoidal vibrations at tolerance levels. Of the 15 symptoms, 9 were chosen to be evaluated by each subject for each frequency run (see figure 2). Since direct quantitative measurements of sensations are impossible, the intensity of each sensation was estimated by each subject, either during or immediately after each run, using a 0 (no uncomfortable or painful sensations) to 4 (the greatest degree of discomfort or pain) appraisal system. If a sensation was vague but not uncomfortable or painful and the subject felt that normal physiological processes were not hindered, the sensation was rated as 0. Since 10 subjects were included in this phase, and 9 sensations were analyzed by the 0 to 4 appraisal system, the greatest possible score for each frequency was 360.

TABLE III
REGIONAL SYMPTOMATOLOGY

HEAD-NECK

Head Sensations	Vibration or "tight" sensation of facial skin
Pharynx	Pharyngeal tug or "lump in throat" etc
Jaw	Sensation of vibration
Speech	Lower frequencies secondarily affected due to reactions of thorax and abdomen, high frequencies due to superimposed transmitted vibrations to laryngeal tissues and possibly main stem bronchi

THORAX

Respiration	Decreased ability to perform physiological respiratory movements of the thoracic cage due to superimposed forces from oscillating platform
Dyspnea	Actual air hunger
Valsalva	Partial or complete closure of glottis resulting in increased intrathoracic and intra-abdominal pressure
Pain	Dull-to-severe pain of the precordium occasionally radiating to the sternum, no other radiations, pain subsiding immediately after cessation of vibration

ABDOMEN

Voluntary Abdominal Musculature Contraction	Degree of contraction or "bearing down"
Pain	Usually periumbilical with tendency to radiate to right lower quadrant

SKELETAL MUSCULATURE

Skeletal Musculature	Sensation of "muscle tightness" or possibly increased muscle tone primarily of the lower extremities, dorsum, and neck
Voluntary Muscle Contraction of Extremities	Muscular contraction in an effort to counteract movements of oscillating platform
Lumbosacral Pain	Dull-to-severe pain at midline with bilateral radiation, subsiding immediately after cessation of vibration

PELVIC-PERINEAL COMPLEX

Micturate (Urge)	Mechanical stimulation of bladder neck and proximal portion of urethra
Defecate (Urge)	Mechanical stimulation of distal portion of sigmoid colon and rectum

GENERAL DISCOMFORT

Overall estimation of each frequency ridden

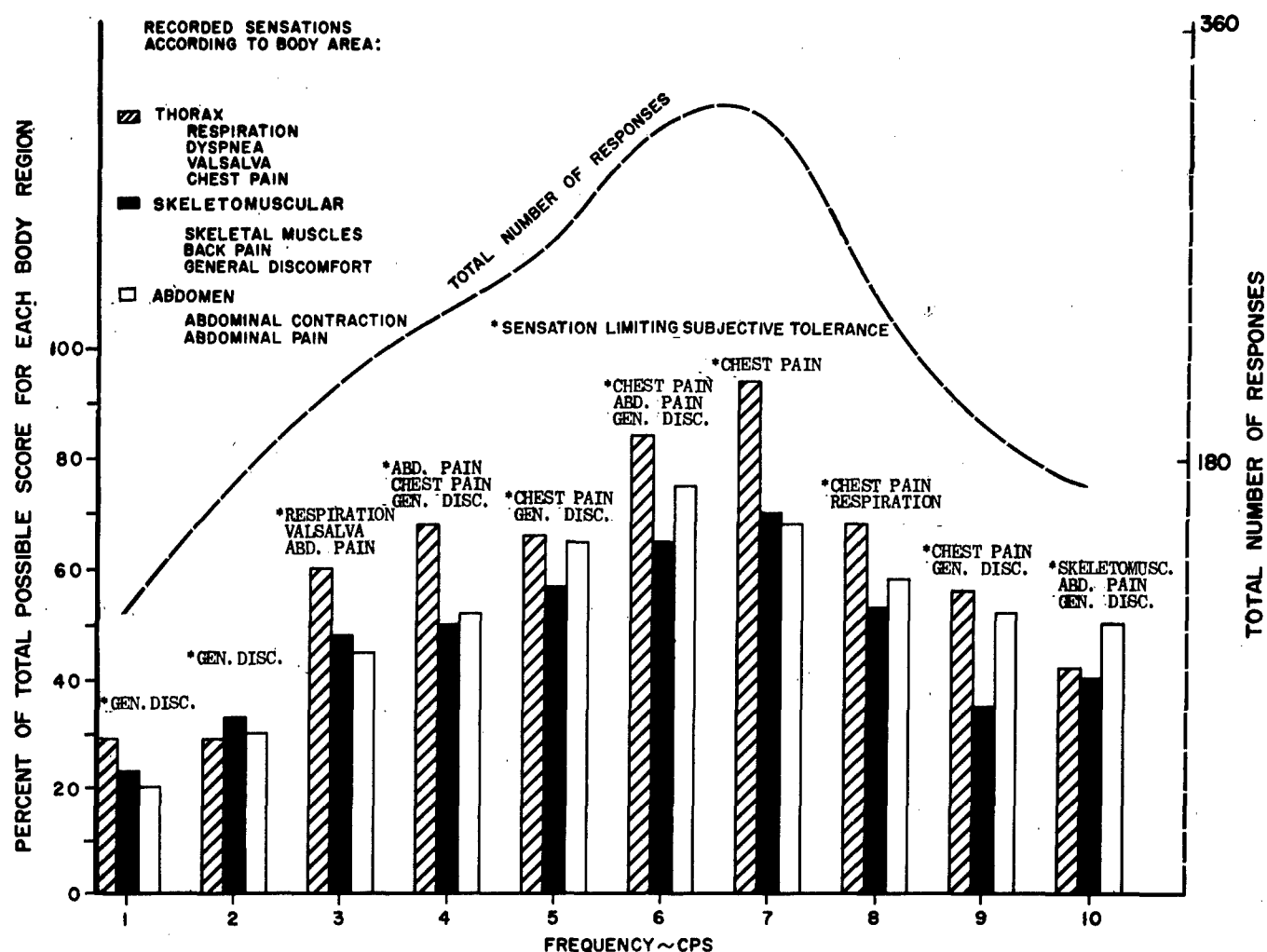


Figure 2. Subjective Response of 10 Subjects (Phase I)

Results

The results are presented in figure 2. A total response curve was compiled representing the sum of all subjective responses for each frequency regardless of the type of symptom. The curve gradually increases from 1 cps to between 6 and 7 cps, and then decreases to 10 cps.

The responses are also classified according to body region: e.g., thorax, abdomen, and skeletal muscles. The bar graph in figure 2 represents the percent of the total possible score for each body region. These responses generally follow the same proportions for each frequency. Between 3 and 7 cps, however, those responses referable to the thorax appear to be somewhat greater than those of the abdomen and skeletal muscles.

Following each run, the subjects gave their impressions of what sensations they regarded as the most severe. This determined their tolerance. These impressions are also incorporated in figure 2. Of these sensations, chest pain at the precordium was reported from 4 to 9 cps inclusive, more than any other symptom.

PHASE II

General

In the first phase, three body regions were investigated collectively. These areas responded to all frequencies, but at different intensities. Many mechanical responses of the body to low-frequency vibrations were demonstrated. In this phase the technique of symptom response was enlarged upon by next classifying each individual symptom quantitatively according to frequency.

Procedure

The 15 symptoms previously mentioned (table III) were included in this study. The 15 subjects had all previously experienced the sensations. Subjective response was classified in terms of moderate intensity and severe intensity. "Moderate intensity" defines those symptoms having an uncomfortable, disturbing, annoying, or moderately painful quality. The intensity of these symptoms would not cause the rider to abort the run. "Severe intensity" defines symptoms of such intensity that much perseverance on the part of the subject is necessary to complete the run. The subjects were asked to estimate the intensities of these symptoms during and immediately after each run.

The frequencies and accelerations studied in this phase are presented in table IV. Frequencies from 1 to 20 cps inclusive were investigated for 1-minute periods at tolerance levels.

The seating arrangement and restraint were the same as in the first phase. The tests were divided into 4 series of 5 frequencies each. The frequencies of each series were staggered and run as in the first phase.

Results

The results are presented in figure 3. Each of the symptoms studied independently fell within a specific frequency range. Generally, the symptoms referable to the thoracoabdominal compartment occurred at the lower frequency range, and the symptoms referable to the head-neck, pelvic-perineal, and skeletomuscular system occurred at the higher frequency range.

Respiration-dyspnea and jaw symptoms both covered three frequencies having the quality of severe intensity with no adjacent range of moderate intensity. All other sensations covered a range of several frequencies beginning as a function of frequency with moderate intensity, becoming severe in intensity, and ending with moderate intensity.

TABLE IV

APPLIED AMPLITUDES AND ACCELERATIONS AT TOLERANCE
LEVELS FOR THE FREQUENCY RANGE OF 1 TO 20 cps
(PHASE II)

1-Minute Study		
cps	G Vector	Double Amplitude (in.)
1	2.4	46
2	2.0	9.5
3	1.5	3.2
4	1.2	1.4
5	0.8	0.61
6	0.7	0.37
7	0.8	0.32
8	1.2	0.36
9	1.4	0.34
10	1.5	0.29
11	1.7	0.27
12	1.9	0.24
13	2.1	0.24
14	2.3	0.23
15	2.4	0.20
16	2.6	0.20
17	2.7	0.19
18	2.8	0.17
19	3.0	0.16
20	3.1	0.15

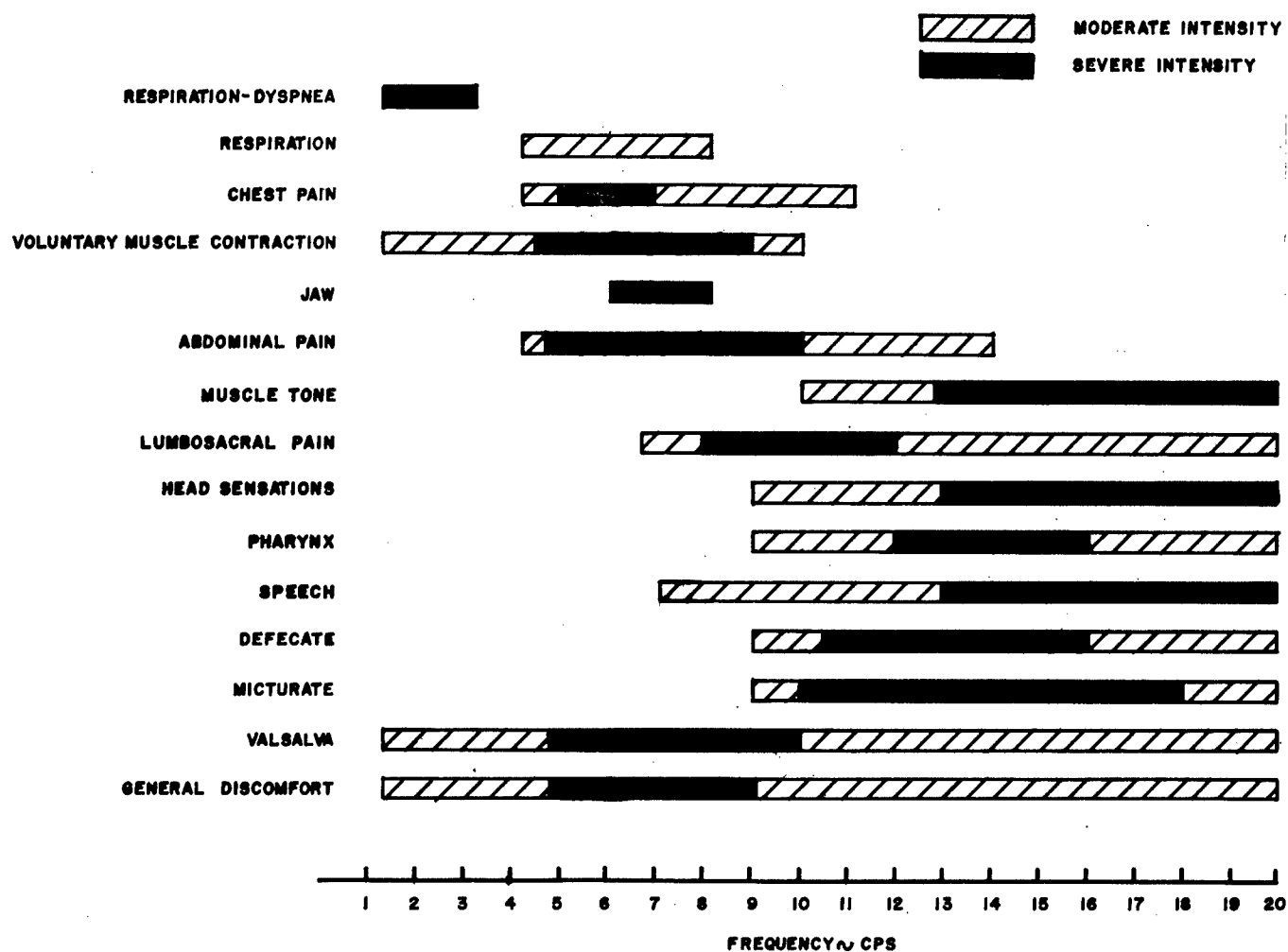


Figure 3. Range of Perceptible Sensations (Phase II)

DISCUSSION

A symptom spectrum has been compiled from identified sensations peculiar to whole-body vibrations at tolerance levels. Subjective responses were measured qualitatively and quantitatively at each experienced frequency. These sensations are the result of alternating mechanical stimulation, either directly or indirectly, upon a profuse complex of sensory receptors representing general somesthetic and visceral sensibility. Mechanical vibration affects only the receptors susceptible to displacement which can be grouped together and referred to as kineceptors: the receptors of touch, pressure, proprioception, and vibratory sensation. Alternating stretching, compression, or deformation of these tissues, individually or combined, may lead to pathological changes of tissues, including contusion, tearing, and rupture. Continued interference with physiological functions, particularly of the respiratory and cardiovascular systems, can lead to irreversible changes.

The highest number of sensations referable to specific body regions was experienced at frequencies between 3 and 9 cps. Sensations in the thorax, growing to severe chest pain at around 7 cps, dominated all other sensations in this frequency range. Sensations of severe intensity referable to the abdominal region also occur primarily at these frequencies.

Similar results were found in the second phase of the investigation. Severe intensity of sensations in chest and abdomen was recorded at frequencies below 10 cps. Additional disturbing jaw movements occurred between 6 and 8 cps. The sensations in the thoracoabdominal organ-tissue complexes produce the most general discomfort between 4 and 9 cps. All other sensations had their severest intensity between 10 and 20 cps. These sensations were referable to organ-tissue complexes located more on the periphery of the body, as muscles, lumbosacrum, head, pharynx, bladder, and perineal organs.

Correlating these sensations with the subjective tolerance curves and the mechanical responses of the whole-body and thoracoabdominal organ complexes, the severest symptoms and the lowest subjective tolerances were observed in the same frequency range as the fundamental natural frequencies of the body. In figure 4 the curves for abdominal wall displacements and thoracic expansion of a subject lying supine on a shake table and being shaken in a longitudinal direction (ref. 1) are compared with the total response curve of phase I. Though the resonance of the thoracoabdominal system in a supine position is around 3 or 4 cps, this resonance will probably be shifted to frequencies around 6 or 7 cps if the subject sits erect in a chair and is restrained by a harness. The mechanical impedance of a sitting subject peaks at about 5 cps (figure 4), indicating that at this frequency the maximum vibrational energy is transmitted to the body. Since the elasticity for this resonance system is mainly in the pelvis, the abdominal mass is most excited at this frequency.

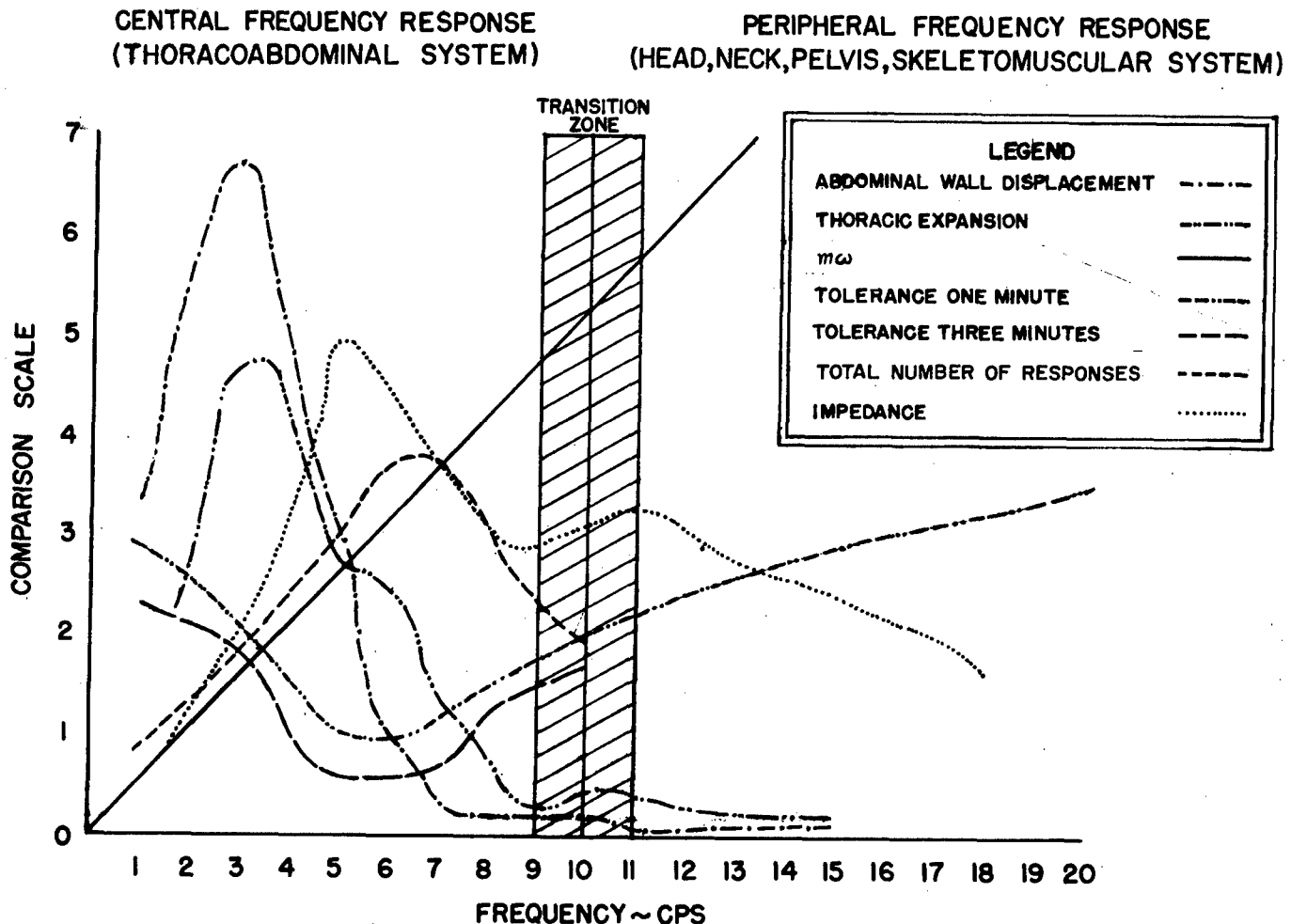


Figure 4. Comparison of Subjective Responses with Mechanical Body Responses (Phases I and II)

Moreover, the subjects experienced a severe chest pain between 6 and 8 cps which must be due to an extreme stretching of tissue in the thorax. Keeping in mind that any severe sensation or pain produced by extrinsic forces applied to the human body must be due to extreme organ displacements, it is not surprising that the lowest tolerances to vibration (figure 4) and the peak of the total number of responses to sensations are in the same frequency range as the resonances in the abdomen and thorax. The organs in these regions have the highest mobility and, therefore, relatively the maximum displacements.

The higher frequencies will mainly affect the organs with higher natural frequencies, those located on the periphery of the body. The head-neck, pelvic-perineal complex, and skeletomuscular systems consist of soft tissue bound down to relatively rigid skeletal structures and are therefore expected to have higher frequencies at resonances above 10 cps. Sensations emanating from the pharynx and pelvic-perineal areas demonstrate possible resonances between 13 and 15 cps. Head sensations and the sensations of increased muscle tone become severe at approximately 13 cps and remain intense up to 20 cps. Since a system with higher natural frequency has less mass displacement per unit of applied acceleration, the tolerable peak acceleration should be higher in the upper frequency range. In addition, the low impedance of the whole body in the sitting position compared with the impedance of a pure mass of the same weight ($m\omega$ -line in figure 4) results in better protection of the total body against higher frequencies. Both effects result in a higher tolerance to vibrations in the frequency range above 10 cps.

As a result of above considerations, the studied frequency range can be divided into two main ranges at approximately 10 cps. The frequencies below 10 cps mechanically excite organ-tissue complexes of the thoracoabdominal compartments and are therefore referred to as the "central frequency range." The higher frequencies affect organ-tissue complexes of the head-neck, pelvic-perineal, and skeletomuscular regions and are referred to as the "peripheral frequency range." Because of anatomical properties, individual differences, and empiricism of subjective introspective observation, from 9 to 11 cps is referred to as the "transition zone" between both components (figure 4).

The concept of central and peripheral components aids in conveniently categorizing the dynamic response of the body to vibrations. The "central frequency range" refers to frequencies wherein lies the resonance of the thoracoabdominal system and the whole-body mechanical impedance. These frequencies are the least tolerable to whole-body vibrations and result in the greatest subjective response. Therefore, resonance, anatomical configuration, tissue mechanical properties, sensory receptor distribution, and characteristics of physiological functions contribute to the low tolerance to vibrational accelerations within this frequency range. The mechanical impedance is an important criterion for greatest physiological stress in a body undergoing vibrations. This concept is useful in all experimentation with vibrations and may aid in a better comparison of studies in both man and animal.

SUMMARY

Symptoms produced by whole-body vibrations are dependent upon physiological alterations brought about by the mechanical responses of various organ-tissue complexes of the body.

Fifteen subjects experienced with whole-body vibrations were included in a two-part study. Ten subjects were included in the first phase. A subjective response of 0 to 4 was obtained for 9 individual symptoms for a 3-minute period at frequencies from 1 to 10 cps at tolerance levels. A curve for total number of responses was derived by summing the total responses for each frequency. The curve peaked between 6 and 7 cps. The total responses were then divided into thoracic, abdominal, and skeletomuscular body regions and represented as the percent of the total possible score for each body region. The symptom of greatest severity for most frequencies occurred at the precordium with no radiation. The body region responses generally follow the same proportional changes for each frequency. This shows that, for each frequency within the range studied, the body presents a multiplicity of reactions, both mechanical and physiological.

In the second phase 15 symptoms were investigated and found to be peculiar to whole-body vibration within the frequency range between 1 and 20 cps. Fifteen experienced subjects were included in this study. Each subject estimated the intensities of the sensations for each frequency. A symptom spectrum compiled from the results suggests that resonance played a role in the physiological alterations brought about by the various body parts.

Mechanical reactivity and subjective response were compared. Main resonances of the thoracoabdominal compartments and their contents occur between 1 and 10 cps and are referred to as the "central frequency range." The head-neck, pelvic complex, and skeletomuscular system respond primarily to frequencies above 10 cps, and are referred to as the "peripheral frequency range." The concepts of central and peripheral frequency range may aid in comparison of studies between man and animal.

RECOMMENDATIONS FOR FUTURE STUDY

This study presents several important problem areas that should be investigated if man is to be exposed to these extrinsic forces. Respiratory, cardiovascular, and cardiopulmonary dynamics, with particular emphasis on pathophysiological processes, should be studied. Also, the nervous system with emphasis on pathophysiological mechanisms of the brain and spinal cord should be ascertained. The mechanical (anatomical) and psychological responses to whole-body vibrations should be investigated for short- and long-time exposures. The mobilization and efficiency of the stressor mechanisms with particular emphasis given to the pituitary-target organ axis should be ascertained.

Some of the phenomena and complexities of body dynamics caused by vibration within the frequency range between 1 and 20 cps have been demonstrated. Much work is necessary to define more accurately the mechanical properties of the body. This study has shown that several areas must be investigated if man is to experience these severe alternating forces. Respiratory, cardiovascular, and cardiopulmonary dynamics during and following vibrations will have to be investigated, particularly for long-time exposures. Special attention should be given to those frequencies exciting the central body components.

Associated with the physiological alterations due to vibration is the psychological manifestation of the individual in anticipation of experiencing and the actual experiencing of these alternating forces. The massive afferent input to the central nervous system during vibration and any residual effects following vibration should be studied. This would include performance and the investigation of possible irreversible changes to the nervous system with emphasis on the brain and spinal cord.

During vibration in the frequency range studied, the body is presented with a severe multiplicity of mechanical stimuli. This has been demonstrated by the present study since several sensations may be simultaneously experienced. These sensations can be obnoxious and may include extreme discomfort and intense pain from more than one region of the body. Exposure to these noxious forces is an immediate threat to body integrity. It is therefore necessary to ascertain the immediate and residual effects of short- and long-time exposures specifically on the mobilization and efficiency of the stressor mechanisms, and generally on the pituitary-target organ axis.

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