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INTERNAL BODY MOVEMENT ALONG THREE AXES RESULTING FROM EXTERNALLY APPLIED SINUSOIDAL FORCES

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THE CHICAGO MEDICAL SCHOOL

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FOREWORD

The information presented in this report was obtained by The Chicago Medical School, Chicago, Illinois, under Contract No. AF 33(657)-10748 for the Aerospace Medical Research Laboratories, under the authority of project 7231, "Biomechanics of Aerospace Operations," and task 723101, "Effects of Vibration and Impact." The responsible investigator in this research was John L. Nickerson, PhD of The Chicago Medical School. In this work, he had the active assistance of M. Drazic, A. Paradijeff, MD, J. Eder, R. Johnson, H. Pevsner, and H. Udesen. The research contained in this report was accomplished during the period of 31 May 1963 to 30 November 1963. Major George C. Mohr of the Vibration and Impact Branch, Biodynamics and Bionics Division, Biomedical Laboratory, served as contract monitor for Aerospace Medical Research Laboratories.

This technical report has been reviewed and is approved.

J. W. HEIM, PhD
Technical Director
Biomedical Laboratory
Aerospace Medical Research Laboratories

INTRODUCTION

The resonant frequencies of internal visceral organs of the dog have been measured in earlier work (ref. 1 and 2) in this laboratory. These experiments were performed upon animals which were anesthetized and fasting, upon animals immediately after feeding, upon animals which were breathing pure oxygen instead of air, and upon animals which were unanesthetized. In all these experiments, the direction of oscillation in which the resonance was determined was the longitudinal (Z) axis of the body. In the present tests, the resonant frequency of a number of organs was measured along X, Y, and Z axes in each animal. The animal chosen for the test was the anesthetized dog.

EXPERIMENTAL METHODS

In these experiments, the dogs used weighed from 10 to 20 kilograms. The animals selected were in good health. Tantalum implants in the form of flat plaques 1 to 2 centimeters square and cylindrical rings 1 centimeter wide were sutured under aseptic conditions in various regions within the animal. The tantalum material was 10 to 15 thousandths of an inch thick. The rings were sutured around the small intestines, and the plaques were sutured to suitable areas of the organs or regions studied.

After recovery from surgery, which was a period of not less than several months, the experiments were performed. The animal was anesthetized with Pentobarbital (32/mgm/kgm of body weight) and by means of a heavy canvas jacket fastened firmly within a plastic cradle attached rigidly to the vibration test stand (ref. 1). The canvas jacket was secured by strong cords in such a fashion that the spinal column of the animal was immobilized. To prevent overheating the animal, cold water was passed continuously through the copper tubing placed within the canvas jacket in such a location as not to obscure the X-ray beam. The cooling arrangement consisted of five 2-foot lengths of copper tubing, 3/8 inch outside diameter and 1/4 inch inside diameter placed side by side and connected in series by rubber tubing at the ends. The tendency of the animal to overheat arose in the higher frequency range of oscillation. By properly adjusting the flow of cold water, it was possible to maintain a constant rectal temperature.

As described in earlier work (ref. 1), the resonant frequency and damping factor for the organ under study was determined by means of a special type of X-ray Kymograph. The X-ray shadow of the tantalum implant and the reference rod on the vibration test stand were cast through a slit in a leaded screen upon a photographic plate which was moving at a velocity of 60 millimeters per second. The oscillation of the vibration test stand produced motions of the implant and of the vibrator reference rod. The motions of the implant and reference rod produced motions of their X-ray shadows along the slit in the leaded screen so that their movements were recorded as oscillating traces on the photographic plate. From these records were made the measurements of the relative amplitude of movement of the implant and of the vibration test table. The phase lag occurring between implant and vibration test table was also measured. The range of frequency tested was from 1 to 10 cycles per second and the amplitude of the vibration test oscillation was maintained at 10 millimeters of double amplitude.

The vibration test stand was a VU-DM-100 L.A.B. Corp. vibration test table. This system could provide oscillations in the desired range of frequency, in horizontal, lateral or vertical directions. With appropriate orientation of the X-ray Kymograph arrangement, it was possible to observe the vibration effects on the dog in supine position along the dorso-ventral or "X" axis, along the lateral right-to-left or "Y" axis, and along the foot-to-head direction or "Z" axis.

Vibration of the animal along the "Z" and "X" axes was made in all cases with the animal in a supine position and with the direction of motion of the vibration test table respectively horizontal and vertical. In all but one case, the vibration along the "Y" axis was observed with the animal lying on its side and the motion of the test table vertical. In the one case, the animal was in a supine position and the vibration was horizontal.

In these experiments, the relative amplitude measurements were made at discrete frequencies in steps of 1 cycle per second or less. In some cases, near the resonant frequency, the steps were reduced to approximately 1/2 cycle per second. This meant that the accuracy of determining the resonance frequency is within 1/2 cycle per second. The procedure in determining the resonance frequency of the region or organ under consideration was as follows: The ratio of movement of the implant to the movement of the reference rod on the oscillation test stand platform was computed for each frequency tested. Of course both movements recorded on the photographic plate were corrected for magnification so that the ratio calculations were from the actual movement in millimeters of the opaque object and of the reference rod. This ratio of relative amplitude was plotted as the ordinate in graphs, Figures 1, 2, and 3, in which the abscissa was the frequency of the forcing oscillation. The point on the graph at which the relative amplitude is maximum is within a few percent of the resonant frequency. Assuming that the oscillating system is of a simple second order type, the true resonant frequency can be computed as follows: The numerical value of the relative amplitude at its maximum point permits the determination from Table 1 of the value of the damping coefficient and the value of the frequency multiplier correction. The product of the multiplier correction and the frequency at the point of maximum relative amplitude gives the value of the true resonant frequency of the region under observation.

TABLE I*

RELATIVE AMPLITUDE, DAMPING AND RESONANT FREQUENCY CORRECTION FACTOR FOR A SIMPLE SECOND ORDER SYSTEM.

Relative Amplitude (At maximum) (Implant/Shaker)	Damping Coefficient	Frequency Correction Multiplier
6.0	0.085	1.001
5.5	0.093	1.002
5.0	0.102	1.002
4.5	0.11[illegible]	1.005
4.0	0.130	1.008
3.5	0.150	1.015
3.0	0.179	1.027
2.5	0.223	1.044
2.0	0.399	1.073
1.5	0.478	1.142

*Table is obtained from reference 2

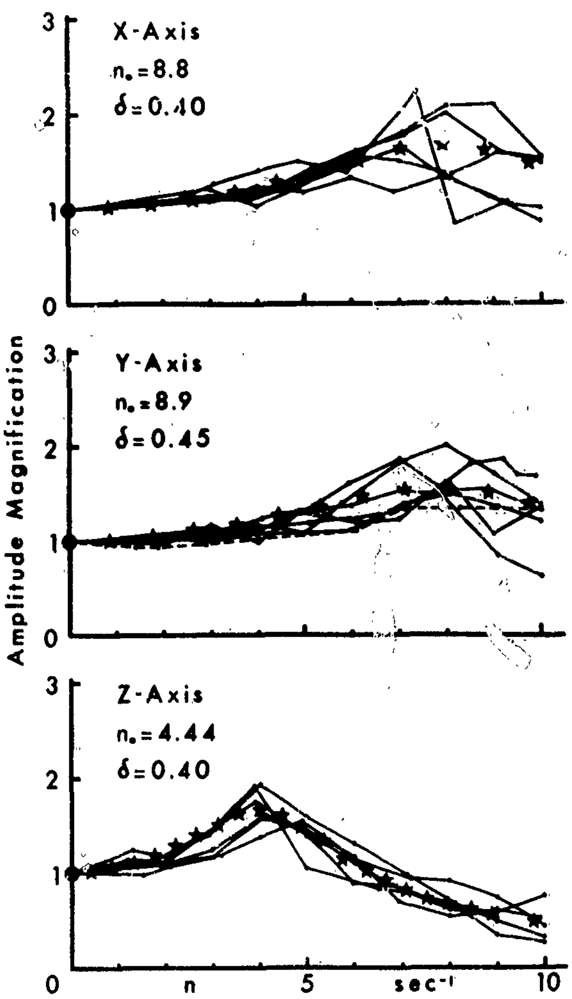

Figure 1.

Graph of relative amplitude response vs. frequency for vibration along three axes. Organs tested: Thoracic aorta, apex of heart, rib, central diaphragm. Stars are points calculated from theoretical equation for values of resonant frequency and damping given in graph.

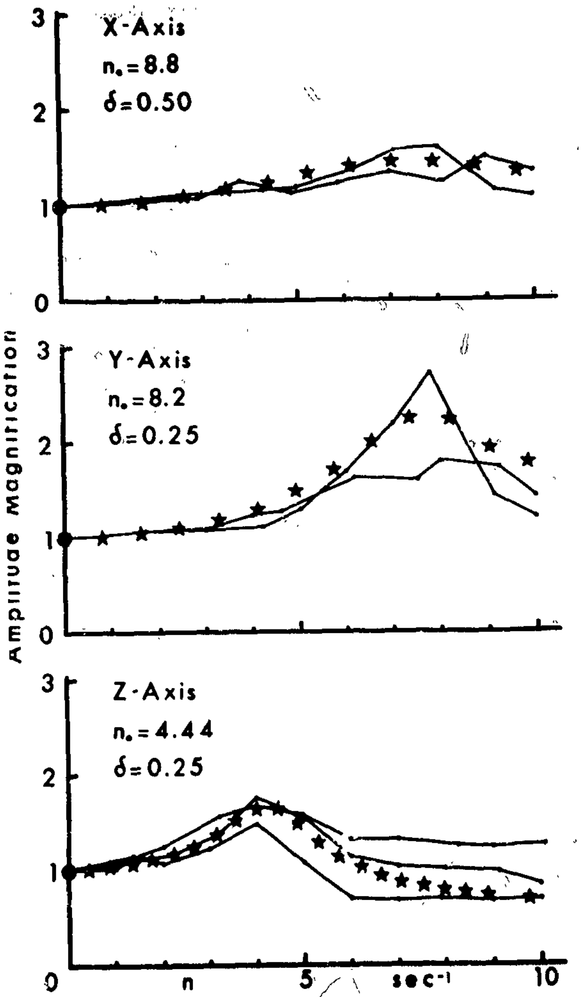

Figure 2.

Graph of relative amplitude response vs. frequency for vibration along three axes. Organs tested: stomach, large intestine, kidney. Stars are points calculated from theoretical equation for values of resonant frequency and damping given in graph.

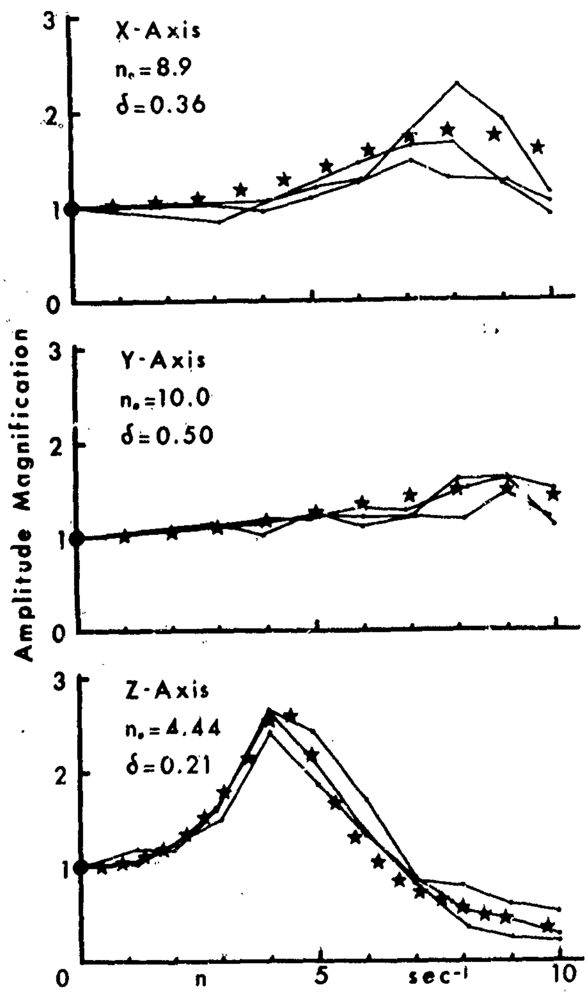

Figure 3.

Graph of relative amplitude response vs. frequency for vibration along three axes. Organs tested: urinary bladder, rectum. Stars are points calculated from theoretical equation for values of resonant frequency and damping given in graph.

Experiments were performed upon nine dogs in some of which were several implants. In several tests, observations were repeated upon the same organ which enabled an estimate of the accuracy of the determination of the resonance frequency. This accuracy is plus or minus 1/2 cycle per second.

EXPERIMENTAL RESULTS

The data for the estimation of the resonance frequencies is presented graphically in figures 1, 2, and 3. In Table II are summarized the values of the resonant frequency of various internal regions as determined from the peak relative amplitudes. The results are illustrated by figure 4. As can be seen both from examination of Table II and figure 4, the resonance frequency of visceral organs along the X and Y axes are essentially the same, being 8.9 and 9.3 cycles per second respectively as averages for all organs. The value along the Z or longitudinal axis has an average value of 4.4 cycles per second, which value agrees very well with the results of the previous experiments on the dog. Since the experimental error of these observations is of the order of 1/2 cycle per second, the difference between mean values of the X and Y axes is not significant. However, the value of the resonant frequency along the Z axis is in all cases significantly different from the values along the X and Y axes.

TABLE II

RESONANT FREQUENCY

ORGAN	AXIS		
	X	Y	Z
Thoracic Aorta	7.7	9.9	4.3
Apex of Heart	9.8	8.2	4.8
Ribs	8.6	9.5	4.3
Central Diaphragm	7.9	8.6	5.0
Stomach	11.0	10.4	4.2
Large Intestine	7.9	10.1	4.2
Rectum	8.0	8.6	4.4
Urinary Bladder	10.3	8.1	4.5
Right Kidney	8.6	10.1	4.2
AVERAGE	8.9	9.3	4.4

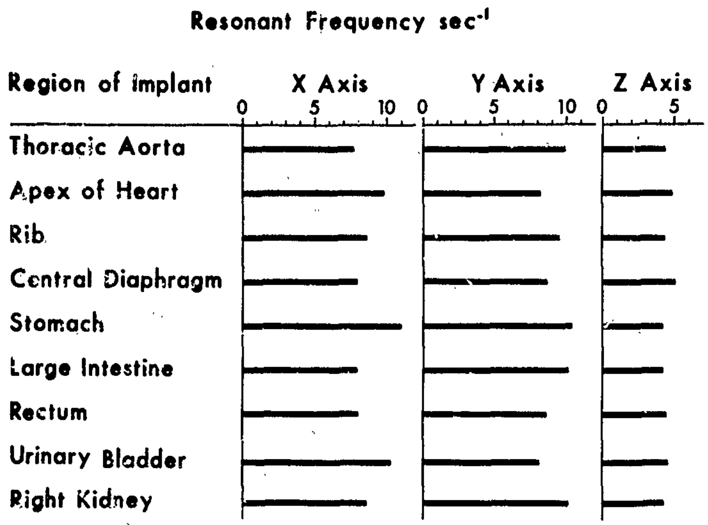

Figure 4. Resonant Frequencies of Various Visceral Regions

The damping coefficients, i. e., ratio of the actual damping to the critical value as found from these experiments are recorded in Table III and in Figure 5. These values are related to the corresponding values in the table of resonance frequency. There is little difference between the mean values of all organs along the X, Y, and Z axes, these values being 0.38, 0.38, and 0.32 respectively. The overall mean value is of the order of 0.36. These values are essentially the same as found for the long axis of the body in previous experimental work.

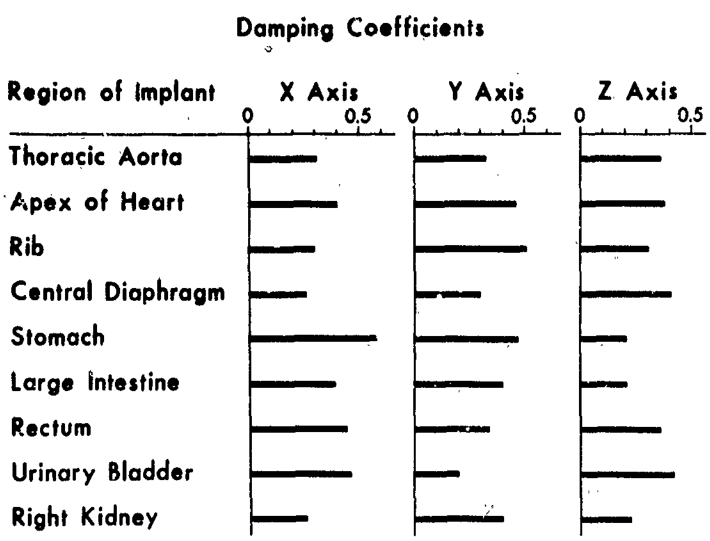

Figure 5. Damping Coefficients of Various Visceral Regions

TABLE III
DAMPING COEFFICIENT

ORGAN	AXIS X	Y	Z
Thoracic Aorta	0.31	0.33	0.36
Apex of Heart	0.40	0.46	0.38
Ribs	0.30	0.51	0.31
Central Diaphragm	0.26	0.30	0.41
Stomach	0.58	0.47	0.21
Large Intestine	0.39	0.40	0.21
Rectum	0.44	0.34	0.36
Urinary Bladder	0.46	0.20	0.42
Right Kidney	0.26	0.40	0.23
AVERAGE	0.38	0.38	0.32

DISCUSSION AND RESULTS

The most marked finding in these experiments was the significant difference in resonance frequency between the measurements from the long axis of the body and the 2 other axes at right angles to this, i. e., the lateral and the dorso-ventral. In the present experiment, the longitudinal resonance frequency values are essentially the same as the longitudinal resonance frequency values found in the previous research reported from this laboratory. However, the lateral and dorso-ventral values are approximately twice as large.

The difference between the resonance frequency in the lateral axes as compared with the longitudinal axis is well founded in the experimental data. This is easily seen from a consideration of figures 1, 2, and 3, which are concerned with the relative amplitude of vibration and of figures 6, 7, and 8 which show the phase lag between implant and forcing oscillation. In these figures, the data is arranged in organ groups from thoracic, abdominal and pelvic regions. Along with the experimental points on each graph are plotted points from a theoretical curve based on the assumption that the motion is of a simple second order type. An estimate of resonance frequency and damping for each group of curves was made, giving a reasonable fit of the data. The results, which in a sense arise from all the data, are summarized in Table IV and are in good agreement with the values on Tables II and III determined from a single point (the point of maximum relative amplitude) in each experiment.

In general, for vibration along a single axis, the results from the various visceral regions are in good agreement except for small differences in damping and possibly a small difference in the resonance frequency in the lateral vibration - between abdominal and pelvic regions. Again, there is a significant difference in resonance frequency for vibration along the longitudinal axis as compared with vibration along transverse axes.

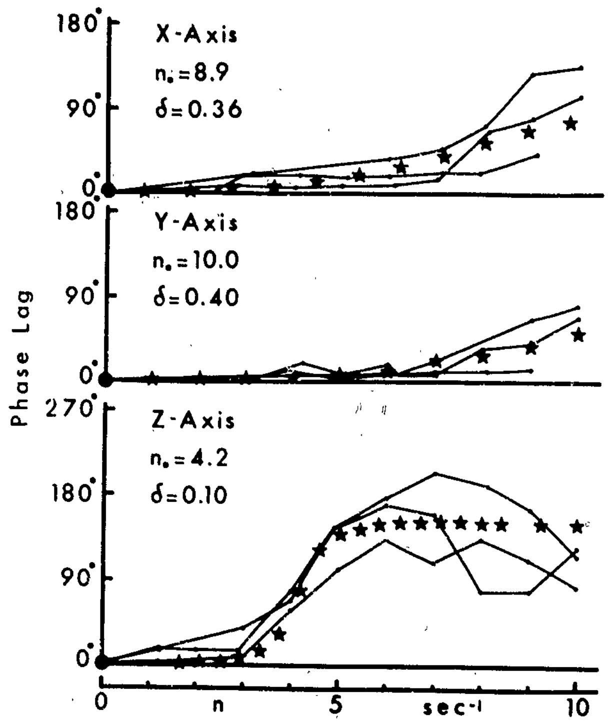

Figure 6.

Graph of phase lag vs. frequency for vibration along three axes. Organs tested: thoracic aorta, apex of heart, rib, central diaphragm. Stars are points calculated for theoretical equation for values of resonant frequency and damping given on graph.

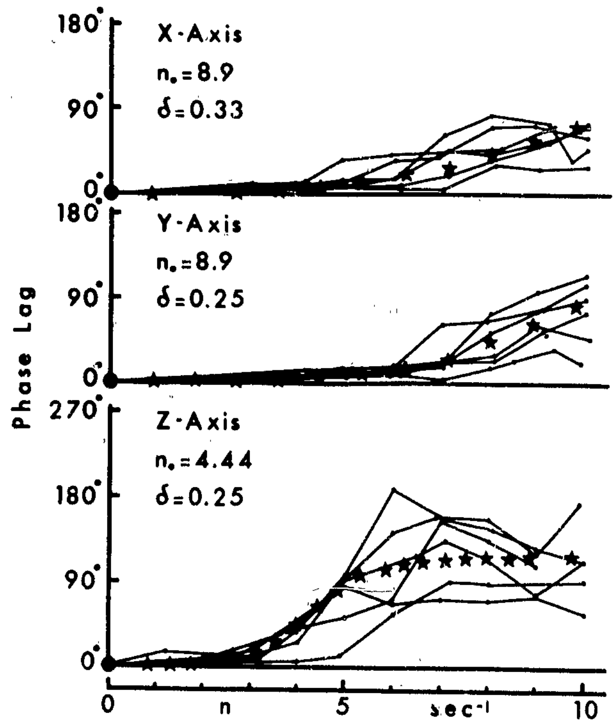

Figure 7. Graph of phase lag vs. frequency for vibration along three axes. Organs tested: stomach, large intestine, kidney. Stars are points calculated from theoretical equation for values of resonant frequency and damping given on graph.

TABLE IV

RESONANCE AND DAMPING BASED ON EACH GROUP OF CURVES IN FIGURES 1 TO 6

	BACK-FRONT X		RIGHT-LEFT Y		FOOT-HEAD Z	
	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase
Thoracic Aorta Apex of Heart Central Diaphragm Ribs	8.8	8.9	8.9	8.9	4.44	4.44
	0.40	0.33	0.45	0.25	0.40	0.25
Kidney Stomach Large Intestine	8.9	8.9	10.0	10.0	4.44	4.20
	0.36	0.36	0.50	0.40	0.21	0.10
Urinary Bladder Rectum	8.8	8.9	8.2	8.2	4.44	4.44
	0.50	0.25	0.25	0.10	0.25	0.50
Weighted Mean	8.9	8.9	9.1	9.1	4.44	4.37
	0.41	0.32	0.43	0.26	0.32	0.25
Overall Mean (Weighted)	8.9		9.1		4.4	
	0.37		0.35		0.29	

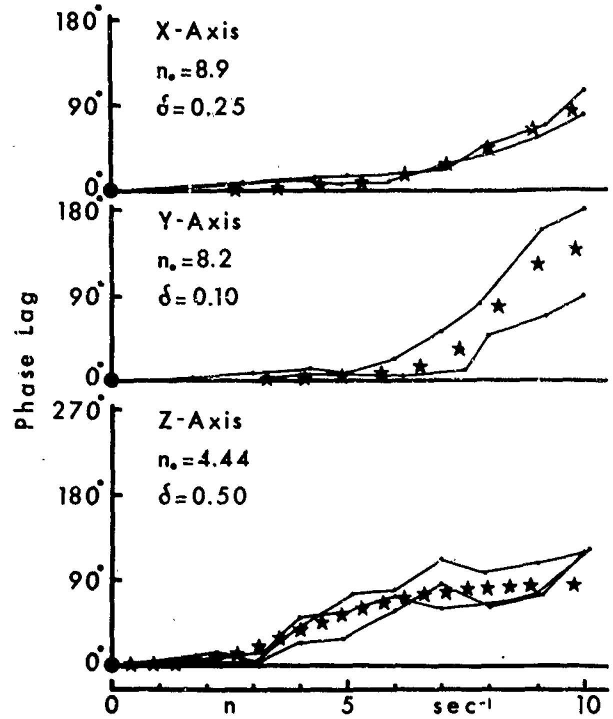

Figure 8.

Graph of phase lag vs. frequency for vibration along three axes. Organs tested: Urinary bladder, rectum. Stars are points calculated from theoretical equation for values of resonant frequency and damping given in graph.

In previous work, (ref. 1), the resonance frequency of 3 to 5 cycles per second of visceral organs in the longitudinal direction was largely determined by the elasticity of the abdomen, since restraining the abdomen raised the resonance frequency.

The observation that resonance frequency along a lateral axis is greater than that along the longitudinal axis indicates an increase in the elasticity to mass ratio. This could be due to a greater involvement of other structures, such as the ribs, in the lateral directions. A further possible explanation would arise if the number of elastic fibers were proportional to the perimeteral length involved in the vibration. Long sides would involve more elastic fibers than short ends, hence lateral motion would be at a higher natural resonance than longitudinal movements.

SUMMARY

In these experiments, the resonance frequency of the visceral organs of the anesthetized dog were measured along 3 axes, namely dorso-ventral, (back-to-front), lateral, (left-to-right), and the longitudinal, (foot-to-head). These resonance frequencies have average values for all these organs respectively of 8.9, 9.1 and 4.4 cycles per second. The values of the damping coefficients associated with these resonance frequencies are respectively 0.37, 0.35, and 0.29.

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This report presents the results of observations on the resonance frequency and damping of a number of internal visceral body structures determined when the whole body is exposed to vibrations along three axes of the body. The X-ray method used is a modification of the system developed earlier. The results, using anesthetized dogs, are as follows. Along the long axis of the body, (Z), the resonance frequency and damping are the average respectively 4.4 cycles per second and 0.29 of the critical value. However, on axes at right angles to the long axis of the body, i.e., the transverse axis, (Y), and the dorso-ventral axis, (X), the values are respectively 9.1 and 8.9 cycles per second for the resonant frequency and 0.35 and 0.37 for the damping factor along the corresponding axes.

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