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Frequency distribution of the heart sounds in normal man[1]

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Authors' synopsis *The magnitude of the heart sounds at various frequencies was studied in 11 normal young men over three areas of the praecordium by using a new calibrated system. The average slope of attenuation for the first heart sound was found to be −6·5 dB per octave at the apex and −7·5 dB per octave at the midpraecordium. A slower decline was found for the second heart sound as the average slope of attenuation of the aortic component at the second left interspace was −6 dB per octave up to 80 Hz and no slope existed between 80 and 140 Hz. The pulmonary component of the second sound at the second left interspace had an overall slope of −3·5 dB per octave. A relative 'peaking' was found in all subjects at different frequencies with the first heart sound usually peaking at lower frequency than the second. Marked variability existed in the slope of attenuation and in the relative peaking between the various subjects. These data are discussed both in terms of physiological considerations and in terms of practical application to the design of equipment.*

Accurate measurements of the amplitude of the heart sounds in man and of the frequency distribution of these sounds are necessary because of both the theoretical implications and the practical applications that can result from this information. The theoretical implications concern the structure and function of the 'cardiohaemic system'. The practical considerations deal with the design of clinical equipment and the interpretation of clinical data.

Methods and materials

This study was conducted on 11 young medical students aged from 21 to 24 yr. All were free from any known cardiac disease and no significant cardiac murmurs were observed on preliminary auscultation. Recordings were obtained from the apex, midpraecordium, and second left interspace of supine subjects with a microphone held in place by a rubber strap. The phonocardiograph used was a new device which has been reported in greater detail elsewhere (MacCanon and Luisada, 1969).

Microphone and filter The response curve of the microphone (Griffen and Tatge, 1969) (General Radio Company 1560-9035) was flat from 10 to 1000 Hz with a threshold of $10^{-3 \cdot 08}$ dyne/cm^2, rms, and a response of 1 V/dyne/cm^2. The output signal of the microphone was introduced, first, into a preamplifier, and then into an operational amplifier differentiating circuit. The differentiators processed the signal so that simultaneous output signals of displacement, velocity, and acceleration with amplification factors of 0, 6, and 12 dB per octave of frequency, respectively could be recorded. The displacement signal was simultaneously introduced into the two sections of a Krohn-Hite filter (Model 3342-R). In one section, low pass filtration at 120 Hz (for low frequency displacement), and on the other section, high pass filtration at 80 Hz (for high pass filtration) was used. The cut-off slopes of the filters were 48 dB per octave. Simultaneous magnetic tape recordings of the heart sounds were made in the lower frequency displacement mode, higher frequency displacement mode, the unfiltered velocity, and the unfiltered acceleration mode. All recordings were made during normal respiration for a period of at least 10 successive heart beats covering at least two respiratory cycles. The recorded signals were then played back, and again passed through the Krohn-Hite, now being employed as a band pass filter. Upon playback, the filter was set so that there was a band of 20 Hz (10 Hz on each side of the nominal frequency) at each of the calibrated sine wave frequencies, described below. The signals were then fed to the oscillograph and recorded on the oscillograph paper.

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Calibration A series of sine waves with known frequencies and amplitudes (as measured on a Tectronix oscilloscope) were generated by a wide range Hewlett–Packard oscillator. The frequencies of the sine wave selected were 30, 50, 70, 90, 110, 130, 150, 170, 190, 210, 310, and 410 Hz.[1] These signals were introduced into the system in place of the microphone signals, and were processed and tape-recorded in the same manner. The various amplitudes of the displacement on the oscillograph tracings were measured as a function of the input voltage. Then, the magnitude of the sine wave deflection on the paper was compared with the measured voltage at the oscillator, and a calibration factor was obtained. At the same time, the gain controls on the preamplifier and on the differentiator amplifier (used to adjust the amplitude of the signals on the oscillograph) were verified as being linear and accurate. The oscillator was then removed and the microphone was repositioned in order to detect heart sounds. The amplitude of the oscillographic record of the heart sounds was converted to a voltage at the microphone output by means of the calibration factor and gain settings. This voltage was in turn transformed into the sound pressure level at the input side of the microphone using the response and sensitivity characteristics of the microphone. Therefore, the sound pressure level of the heart sounds was determined from the magnitude of the deflection on paper, on the basis of calibration and gain factors of the system as determined from the sine wave procedure (see Appendix).

Measurements The sound pressure of each of the frequency bands below 100 Hz was determined by use of the displacement recordings; above 100 Hz, by use of the velocity recordings. This discrimination was necessary because of certain aspects of amplification inherent to the heart sounds and to the recording technique. The lower frequency sounds were well displayed by use of the displacement tracing while the higher ones were better revealed by the velocity tracing, due to the characteristics of the differentiating circuit.[2] The deflections caused by the first and second heart sounds were measured in millimeters, and the results were transformed into sound pressure levels, expressed as dyne/cm^2, or as dB with respect to $4\sqrt{2}\times10^{-4}$ dyne/cm^2 peak-to-peak (which was derived from the accepted standard rms sound pressure level of 2×10^{-4} dyne/cm^2). The calculations involved in this study are described below.

[1] The bands studied were adjoining bands from 20–40 Hz to 400–420 Hz. Lower bands were not studied because of difficulty in recognizing single waves coinciding with the heart sounds.

[2] The validity of employing two different modes of measurement – that is, displacement amplitude for the lower frequency bands and velocity amplitude for the higher frequency bands – was evaluated. The frequency bands of 60–80 Hz, and 80–100 Hz allowed simultaneous measurement of both displacement amplitude and velocity amplitude. The results of calculating the sound pressure level from each of these modes was compared. The ratio of the displacement value to the corresponding velocity value was calculated for each of 70 heart sounds. The average ratio was 1·004, with a standard deviation of 0·096. These figures indicate that the results from displacement recordings were consistent with those from the corresponding velocity recording within the range of experimental error expected in this study.

Recording areas The microphone was applied in succession to three recording areas: (1) the area centering on the point of maximal impulse (4th–5th left intercostal space at the midclavicular line); (2) the midpraecordium (3rd–4th left intercostal space half-way between apex and sternal border); and (3) the base (2nd–3rd left intercostal space at 2–4 cm from the sternal border). These areas were selected after previous studies from this laboratory (Shah, Slodki, and Luisada, 1964) indicating that all pertinent information will be obtained by their use.

Results

The average values of the heart sound pressure levels in each frequency band are shown in Table 1. The magnitude of the heart sound pressure levels was greatest in the 20–40 Hz band, and then gradually decreased from the lower to the higher frequency bands regardless of the location from which the sound was obtained. The largest peak-to-peak magnitude of vibrations of the series was in the 20–40 Hz band and was equivalent to 36·1 dB ($35{\cdot}92\times10^{-3}$ dyne/cm^2). The standard deviation was large indicating great individual variability.

First heart sound (I)[1] In general, the magnitude of the first heart sound vibration decreased with an increase of frequency (Figs. 1, 2, and Table 1). The average slope of the attenuation was $-6{\cdot}5$ dB/octave at the apex, $-7{\cdot}5$ dB/octave at the midpraecordium, and $-8{\cdot}5$ dB/octave at the second left interspace. The sound pressure distribution over the frequency spectrum showed an extreme individual variability in pattern (Table 2). However, this variability was least at the midpraecordium. When the intensity of I was analysed at the three microphone locations for the various frequency bands, it was noted that the intensity tended to show a relative maximum in the lower frequencies at the midpraecordium, and in the higher frequencies at the apex.

Second heart sound (II) As for the first heart sound, the intensity level of the second sound

[1] This and the following abbreviations are consistent with the *International Standardization of Phonocardiographic Symbols* (Holldack, Luisada, and Ueda, 1965).

TABLE I *Mean values and standard deviation of heart sounds in 11 young males*

	Apex				*Midpraecordium*				*Second left interspace*					
	I		*IIA*		*I*		*IIA*		*I*		*IIA*		*IIP*	
Frequency band (Hz)	*dB*	*dyne cm²* *(SD)*	*dB*	*dyne cm²* *(SD)*	*dB*	*dyne cm²* *(SD)*	*dB*	*dyne cm²* *(SD)*	*dB*	*dyne cm²* *(SD)*	*dB*	*dyne cm²* *(SD)*	*dB*	*dyne cm²* *(SD)*
20–40	35·0	31·94 (23·99)	30·0	17·96 (7·80)	36·1	35·92 (16·55)	34·1	28·65 (13·29)	34·5	29·56 (24·19)	31·9	22·31 (18·60)	27·5	13·45 (4·95)
40–60	29·2	16·43 (7·64)	26·8	12·44 (3·51)	30·9	19·96 (12·34)	30·3	18·54 (9·77)	28·1	16·05 (12·77)	27·7	13·76 (9·16)	25·6	10·86 (5·85)
60–80	28·2	14·56 (7·58)	26·7	12·30 (4·30)	27·6	13·48 (7·89)	27·9	14·07 (7·19)	24·0	9·00 (5·05)	24·3	9·38 (5·97)	25·0	10·10 (4·76)
80–100	25·8	11·03 (7·50)	25·6	10·80 (4·71)	24·0	9·05 (4·14)	25·9	11·10 (5·49)	21·1	6·40 (2·89)	22·1	7·20 (2·46)	20·4	7·90 (3·60)
100–120	23·1	8·04 (4·54)	24·5	9·52 (3·99)	21·1	6·44 (2·45)	24·7	9·71 (4·08)	18·6	4·81 (1·48)	21·7	6·86 (1·89)	20·1	5·73 (2·26)
120–140	22·3	7·36 (4·34)	23·9	8·91 (3·60)	19·5	5·33 (1·47)	23·7	8·67 (4·23)	17·2	4·08 (0·91)	21·9	7·02 (2·20)	20·1	5·70 (2·28)
140–160	20·4	5·90 (3·98)	20·7	6·15 (3·03)	17·4	4·20 (1·25)	21·9	7·04 (2·52)	15·9	3·51 (0·66)	20·8	6·17 (1·70)	18·6	4·83 (1·98)
160–180	20·5	5·98 (4·20)	20·8	6·21 (2·33)	17·1	4·04 (0·96)	21·0	6·35 (1·79)	16·0	3·55 (0·81)	20·1	5·74 (1·13)	19·0	5·06 (2·52)
180–200	20·1	5·74 (4·45)	19·8	5·52 (1·77)	16·4	3·72 (0·94)	19·8	5·55 (1·67)	15·5	3·37 (0·75)	18·7	4·88 (1·02)	18·4	4·70 (2·40)
200–220	18·4	4·73 (3·53)	18·0	4·47 (1·18)	15·5	3·38 (0·84)	18·6	4·81 (1·69)	14·5	2·99 (0·68)	17·4	4·17 (1·02)	17·6	4·29 (2·24)
300–320	15·5	3·38 (1·74)	14·4	2·95 (0·35)			14·7	3·08 (0·48)			15·4	3·31 (0·41)	14·3	2·94 (0·72)
400–420							13·4	2·64 (0·24)			13·4	2·65 (0·18)		

I = First heart sound: *IIA*, *IIP* = Aortic, pulmonic component of second heart sound.
dB = decibels with respect to $4\sqrt{2} \times 10^{-4}$ dyne/cm². *SD* = Standard deviation in dyne/cm².

decreased in general from the lower to the higher frequency bands (Table 1, Figs. 1–3) but its decline was slower than for the first heart sound.

The aortic component of the second heart sound (*IIA*) at the apex declined in intensity with an average slope of −3·5 dB/octave between 20 and 140 Hz, and with an average slope of −8·0 dB/octave between 140 and 320 Hz showing a gentle 'peaking' between 60 and 220 Hz. At the midpraecordium, IIA showed a −5·2 dB/octave slope between

FIG. 1 *Amplitude of the first heart sound* (I) *and of the aortic component of the second heart sound* (IIA) *at various frequencies as measured at the apex. Mean values for the entire series. Comparison with the −12 dB/octave slope.*

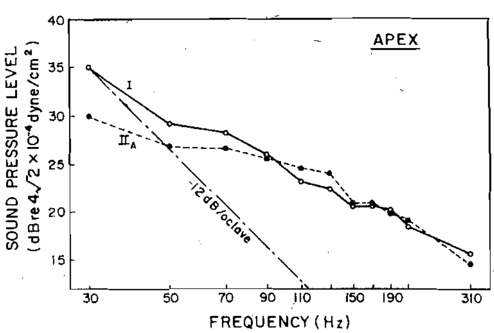


FIG. 2 *Amplitude of the first heart sound* (I) *and of the aortic component of the second heart sound* (IIA) *at various frequencies as measured at the midpraecordium. Mean values for the entire series. Comparison with the −12 dB/octave slope.*

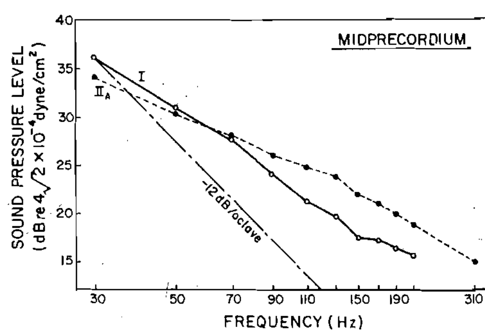


TABLE 2 *Point of maximum of first heart sound*

Frequency band (Hz)	*Number of times maximum intensity noted at each location*		
	Apex	*Mid-praecordium*	*Second left interspace*
20–40	1	7	2
40–60	2	8	1
60–80	6	5	0
80–100	5	6	1
100–120	7	4	0
120–140	7	4	0
140–160	9	2	0
160–180	9	2	0
180–200	9	2	0
200–220	9	2	0
300–320	9	2	0

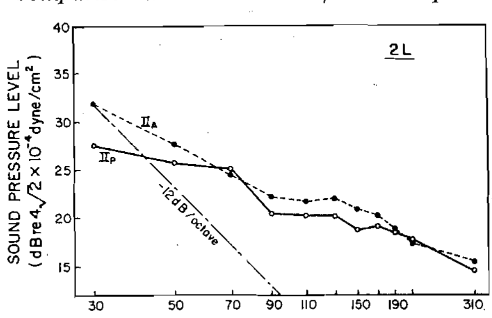
TABLE 3 *Point of maximum of second heart sound*

Frequency band (Hz)	*Number of times maximum intensity noted at each location*		
	Apex	*Mid-praecordium*	*Second left interspace*
20–40	2	7	2
40–60	3	7	1
60–80	6	4	1
80–100	4	5	2
100–120	3	8	0
120–140	5	4	2
140–160	6	3	2
160–180	5	4	2
180–200	2	5	4
200–220	2	5	4
300–320	3	4	4

20 and 140 Hz, and a −7·0 dB/octave slope between 140 and 320 Hz. The curve of IIA at the second left interspace had an average slope of −6·0 dB/octave, except that it was flat between 80 and 140 Hz (Table 3, Figs. 1–3). There was notable individual variability. However, the least variability seemed to be at the apex, not over the midpraecordium as for the first heart sound. The maximum intensity level of IIA below 180 Hz was usually at the midpraecordium, followed by the apex, and then by the second left interspace. On the contrary, the maximum intensity level of this component above 180 Hz was usually at the midpraecordium, followed by the second left interspace, and then by the apex.

The pulmonary component (IIP) of the second sound at the second left interspace showed an average overall slope of −3·5 dB/octave (Table 1, Fig. 3).

FIG. 3 *Amplitude of the aortic component* (IIA) *and pulmonary component* (IIP) *of the second sound at various frequencies as measured over the second left intercostal space. Mean values of the entire series. Comparison with the −12 dB/octave slope.*



Intensity comparison of heart sounds In general the aortic component of the second sound (IIA) was greater than I in magnitude at the higher frequencies (Figs. 1–3). The frequency above which IIA was noted to be greater than I in more than seven out of 11 cases was 120 Hz at the apex, 80 Hz at the midpraecordium, and 60 Hz at the second left interspace (Table 4). The intensity level of the pulmonic component of the second sound (IIP) was usually less than that of the aortic component (IIA) at the second left interspace in each of the 20 Hz frequency bands studied (Table 1, Fig. 3).

Relative maxima ('peaking') of heart sounds In the frequency distribution curves of the heart sounds, there was no clear correlation between the frequency at which peaking occurred from subject to subject. Relative

TABLE 4 *Intensity comparison of I and IIA*

Frequency band (Hz)	*Number of times IIA noted to be greater than I*		
	Apex	*Mid-praecordium*	*Second left interspace*
20–40	2	3	2
40–60	4	6	5
60–80	4	6	8
80–100	4	7	7
100–120	5	8	9
120–140	7	9	10
140–160	7	9	10
160–180	7	9	10
180–200	8	9	10
200–220	9	9	10
300–320	7	9	10

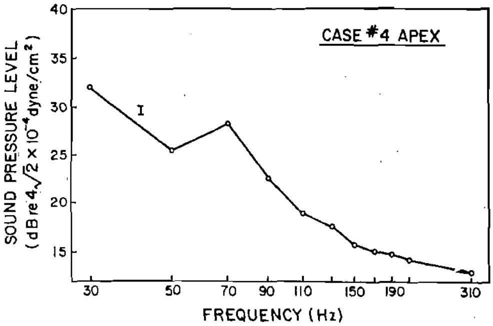


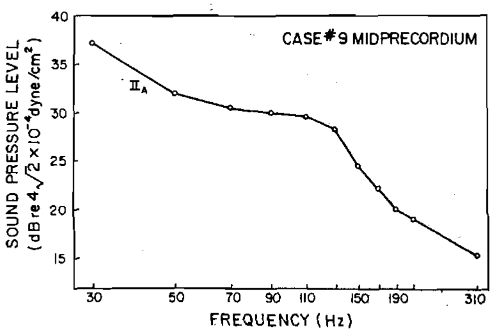
FIG. 4 *Amplitude of the first heart sound* (I) *at various frequencies as measured at the apex in a representative case.*

maxima or peakings were observed to occur in the individual cases anywhere between 50 and 210 Hz. However, the curves of the first heart sound had a tendency to show 'peaking' at lower frequencies than those of the second heart sound. This phenomenon of peaking is much less obvious in the average curves (Figs. 1–3) than in those of individual cases, due to individual variations for each subject. This is clearly shown by representative tracings (Figs. 4, 5).

Discussion

There have been numerous attempts to study the relative magnitude of the normal heart sounds at various frequencies since the study of Mannheimer (1957), the most significant being those of Maass and Weber (1952) and McKusick, Talbot, and Webb (1954). Following the study of Maass and Weber (1952), Holldack (1952) accepted that the heart sounds decrease in terms of frequency according to the 'inverse law of the square', a theoretical physical law resulting in a curve of -12 dB/octave. Several commercial phonocardiographs have an automatic gain increase for higher frequencies based on this law. However, actual observation with calibrated equipment had shown one of the authors (Luisada, Inoue, and Katz, 1963) a lesser and non-uniform decrease.

FIG. 5 *Amplitude of the aortic component of the second heart sound* (IIA) *at various frequencies as measured over the mid-praecordium in a representative case.*



Our results have revealed that the largest vibrations were in the 20 to 40 Hz range, even though there were individual variations. After this, there was a gradual decrease which was faster or slower in various subjects, with 'peaking' at one or more points according to the individual.

In general, the drop in amplitude from increasing frequency was somewhat slower above 150 Hz and even more so above 210 when sounds were still recorded.

The mean values indicated a smaller amplitude of the second sound at low frequency in comparison with the first, and a greater amplitude at frequencies above 70 to 90 Hz. In regard to the second sound itself, the pulmonic component had a smaller amplitude than the aortic component at low frequencies (below 70 Hz) and disappeared at high frequencies, while the aortic component was still recorded. Around 70 Hz, the aortic and pulmonary components had the same magnitude.

By comparing these curves of amplitude versus frequency with the attenuation curve of 12 dB/octave that has been considered as typical, we can see that the heart sound becomes smaller with increasing frequency but much less than the 12 dB/octave curve. Therefore, current phonocardiographs which have an automatic gain of 12 dB/octave will tend to over-emphasize the sounds in the high frequency bands. Moreover, as such automatic gain cannot take into account the relative peaking, it would tend to over- or under-amplify certain bands in the various individuals. The 'inverse law of the square' – that is, -12 dB/octave – was based on the assumption that the sound generator (heart) would originate vibrations of the same power at all frequencies. The fact that the attenuation of sounds with increasing frequency does not coincide with such a physical law can be explained in two ways. (1) The heart as a sound generator creates vibrations of various frequencies according to its own characteristics; some are larger than when a single frequency is experimentally generated. (2) The attenuation caused by tissue transmission and possible resonance may tend to emphasize certain frequencies.

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Appendix

Calculations When the magnitude of a sound or sine wave tracing is D mm peak-to-peak, with d mm the width of the tracing on the paper, and F the gain factor of the system, the calibration factor (f) for the centre frequency of the pass band is given by the formula, $A = f \times (D - d)F$, where A is the corresponding output of the microphone in volts. The microphone threshold is $10^{-3.08}$ dyne/cm², or $2\sqrt{2} \times 10^{-3.08}$ dyne/cm² peak-to-peak, and the response is 1 V/1 dyne/cm² rms or peak-to-peak. Therefore, when the output of the microphone is A volts peak-to-peak, the corresponding input sound pressure level is given by the formula, P (dyne/cm²) $= 2\sqrt{2} \times 10^{-3.08} A$. The corresponding sound pressure level of the reading of A volts converted to decibels is given by the formula, $N(dB) = 20 \log (P/4\sqrt{2} \times 10^{-4})$, where $4\sqrt{2} \times 10^{-4}$ dyne/cm² peak-to-peak is derived from the rms sound pressure level of 2×10^{-4} dyne/cm², which is commonly used as a standard. When the output of the microphone is zero, the input signal is less than, or equal to $4\sqrt{2} \times 10^{-3.08} = 2{\cdot}353 \times 10^{-3}$ dyne/cm² peak-to-peak. This value can be converted to 12·38 dB with respect to $4\sqrt{2} \times 10^{-4}$ dyne/cm² peak-to-peak. This means that sounds with an intensity level less than $2{\cdot}353 \times 10^{-3}$ dyne/cm² or 12·38 dB are not detected by the microphone used in this study.