Damping of Sound on the Chest Surface

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A number of investigators have recently studied how heart sounds and murmurs spread through the various tissues of men and dogs. For instance, Magri et al. studied the transmission of heart sounds over the surface of the exposed human heart. Kerr and Harp, Kerr et al., and ourselves investigated the velocity and the damping with which sound is transmitted through arteries, and showed that this transmission is in the form of pulse waves.

On the surface of the body, the velocity of conduction of the heart sounds was found to increase with the square root of the frequency and to be only about 15 m/sec for the 100 cycles/sec component. The auscultatory areas were found to act as secondary sources. Dunn and Rahm recorded the amplitudes of the heart sounds at various points on the chest wall. However, the damping of sound during its transmission over the surface of the chest has, to our knowledge, not yet been measured.

In the present experiments, we applied an external source of sound to the skin of the thorax. This was a more convenient source of single frequencies than heart sounds. There are also fundamental objections to the use of heart sounds for the purpose of measuring the damping of sound, as both the first and the second heart sounds are mixtures of sounds from multiple sources.

The wave lengths of sounds on the surface of the chest can be calculated from our data. They are about 15 cm for frequencies of 100 cycles/sec, and about 10 cm for frequencies of 200 cycles/sec. The interference pattern of these sounds from multiple sources probably changed the amplitude from place to place on the chest and thus accounted for our failure to get interpretable results with heart sounds, even if narrow frequency bands were used.

In theory, the continuous sound produced by the external source could create standing waves if the vibrations travelling over the body surface are reflected from some structure in the chest wall. If this happens, the apparent attenuation of the sound should be somewhat less than the true attenuation. However, the magnitudes of the attenuations that were found suggested that standing waves did not exist, or that their influence on the attenuation was negligible.

Methods

The experiments were done on human males in a small soundproof room. An Electro-Voice DC30A loudspeaker driver rated at 20 watts served as a source. A brass pipe of 35 mm internal diameter mounted on the driver and closed with a rubber stopper conducted the sound to the surface of the body. The entire unit except the end of the brass pipe was cast in a block of concrete. No sound emerged from the unit except through the rubber stopper. A Heathkit AG-5 audio oscillator produced a sinusoidal signal of a single frequency which was amplified by a Paco SA-40W power amplifier and fed into the driver. The rubber stopper of the driver was glued to the skin of the chest.

Signals were recorded with a small Armaco MCT-A crystal throat microphone and amplified by a Tektronix 122 low-level preamplifier. The intensity of the signal emerging from this amplifier was measured by a General Radio 760-B sound analyzer. This analyzer measured the intensity of a single frequency relative to an arbitrary reference level. The relative rejection of other frequencies was three decibels for frequencies at 1% off the peak to which the analyzer was tuned and more than 35 decibels at one octave difference. The range of the meter was 25 to 7500 cycles/sec, and it could measure intensities in a range of 42 decibels.

Selected frequency was set on the dial of the sound analyzer and the audio generator was then tuned until the output of the analyzer was maxi-
DAMPING OF SOUND ON THE CHEST SURFACE

The microphone was not calibrated. Hence, all sound levels measured in this study were relative to some arbitrary level chosen at the beginning of each experiment. Intensity of the sound emerging from the driver was adjusted to a level that was just sufficient to drown interference by the heart sounds, so that the output of the sound analyzer remained steady during the heart cycle.

The area on the body surface that was investigated was a square of 14 by 14 cm in the middle of the body with its top at the level of the angle of Louis (fig. 1). The relative intensities of the sound were measured at 25 points in this square, i.e., at 3.5 cm intervals. Small squares of surgical tape (1 cm by 1 cm) glued to these points served as a base for the microphone. The microphone was glued to each of these squares in succession. The presence of the surgical tape did not change the observed damping. The sound intensity at one of these points was measured several times during the experiment to verify that the intensity of the sound produced by the driver, and the gain of the recording equipment had not changed. Frequencies of 50, 70, 100, 200, and 400 cycles/sec were investigated.

The source of sound was usually placed on the sternum at the lower edge of the field shown in figure 1. However, in experiment 1 it was placed further to the right of the precordium (fig. 3) and in experiment 3 it was placed on the auscultatory area of the mitral heart sound. These experiments gave results that were very similar to the results from the other experiments.

Damping can be shown most clearly with charts of equal intensity contour lines (figs. 2 and 3). The first contour line on the chart was drawn through a “reference point” located on the midline of the precordium 3.5 cm above the bottom of the field. The other contour lines were then drawn at intervals of five decibels, a reduction of the intensity to about one-third. The contour lines were obtained by linear interpolation between the points at which the intensities had been measured. Only slight smoothing of the curves was necessary, as can be seen in figures 2 and 3.

Twenty such contour maps were drawn from the results of six experiments on four subjects. No experiments were discarded. The field used in the first experiment was somewhat different from the field used in the other experiments (fig. 3).

Results

The results of experiments 1 and 5, shown in figures 3 and 2 respectively, are representative. The number of five-decibel contour lines per field is a measure of the degree of damping. Since each line on the chart represents a damping of five decibels, the damping is greatest in the areas where the lines are closest together. Table 1 shows the number of five-decibel contour lines for each of the twenty charts. The values from table 1 are shown graphically in figure 4.

The chest wall is clearly unhomogenous. For frequencies above 100 cycles/sec the sternum is a much better conductor than soft tissues or ribs. The increase with frequency of the number of five-decibel contour lines per chart is mainly a property of the soft tissues as the number of contour lines on the sternum does not increase nearly as much. The increase in damping appeared to be approximately linearly related to the square root of the frequency; this could later be proved.

The coefficient of linear correlation between the number of five-decibel lines per chart and the square root of the frequency is 0.81. The
FIGURE 2
The five-decibel contour lines from the results of experiment 5 for frequencies of 50, 100, 200, and 400 cycles/sec. Numbers indicate how many decibels the intensities were below an arbitrary level of intensity.

probability that this correlation was entirely due to random errors is much less than 0.01. The regression equation which predicts the number of five-decibel contour lines per chart is

\[ N = 1.13 + 0.44 (f)^{1/2} \]  

where \( N \) is the number of five-decibel contour lines and \( f \) is the frequency in cycles/sec. In equation 1, the standard error of 1.13 is ± 0.89 and the standard error of 0.44 is ± 0.075.

The number of five-decibel contour lines per chart was one too many, as the first line did not represent any damping. It could always be drawn even if there was no damping at all. Thus, the number of five-decibel contour lines per chart overestimated the total damping by five decibels.

On the other hand, there could have been between zero and five decibels more damping than was shown by the number of contour lines because a five-decibel line was drawn only if there was a complete step of five deci-
FIGURE 3

The five-decibel contour lines from the results of experiment 1 for frequencies of 50, 100, and 200 cycles/sec.
The number of five-decibel contour lines per chart, plotted against the frequency in cycles/sec on a square root scale. Regression equation 1 is shown by a line.

The true attenuations occurring in the field studied are, therefore, an average of 2.5 decibels less than the values shown in table 1 and figure 4. When equation 1 is multiplied through by five to give the damping in decibels per field, and corrected by 2.5 decibels, the regression equation becomes

\[ n = 3.15 \pm 4.46 + 2.20 \pm 0.375 \times (f)^{1/2} \]  

where \( n \) is the damping in decibels per field.

**Discussion**

A sound which spreads through a medium is attenuated both by the viscosity of the medium and also by its spread into a larger volume, e.g., the intensity of a sound in a gas or a liquid is proportional to the inverse of the square of the distance from its source provided the additional viscous damping is negligible.\(^{13}\) It seems reasonable to speculate that the term 3.15 which represents a frequency independent damping in equation 2 is such a geometrical factor.

Our earlier experiments\(^{6}\) indicated that heart sounds travel over the surface of the chest, and thus spread in a plane rather than in a volume. Therefore, the geometrical part of the damping was expected to be proportional to the distance, rather than to the distance squared.

In the charts, the distance from the source to the reference point through which the first five-decibel contour line was drawn is about one quarter of the largest possible distance from the source to any point in the field. Therefore, the geometrical term should be about 12 decibels \((10 \times \log 16)\) if there is an inverse square relationship between distance and intensity. But if there exists an inverse linear relationship between distance and intensity, the geometrical term should be only about six decibels \((10 \times \log 4)\). The value of 3.15 decibels with a standard error of 4.46 decibels in equation 2 makes a value of 12 decibels unlikely \((P = 0.07)\). But the value of 3.15 decibels is not significantly different from 6.0 decibels \((P = 0.5)\) and thus supports our view that sounds on the chest wall travel in a plane.

Once the geometrical contribution to the damping was found to be about six decibels, the values in table 1 could be corrected for this and also for the overestimate of 2.5 decibels discussed above. It could then be shown by logarithmic transformation of the dependent and independent variables (damping and frequency respectively) that the damping was predicted best by the 0.70th power of the frequency. The standard error of this value 0.70 is \(\pm 0.12\). This power is not significantly different from the power 0.50 assumed after inspection of the results which gave a coefficient of correlation of 0.81. This square root relationship is interesting in view of the observation that the velocity of conduction of heart sounds on the chest wall is also proportional to the square root of the frequency.\(^{5}\) It happens that the damping per wave length has an approximately constant value of 27 \(\pm 4.6\) decibels (see Appendix).

As the damping per centimeter increases with the square root of the frequency, the heart sounds must be distorted considerably during their transmission over the surface of the chest. This explains the change in character of heart sounds during their transmission over the surface. Determinations of the frequency spectrum of heart sounds are not completely defined unless the point at which the sounds are recorded is specified, as well as their point of maximum intensity, the secondary source on the chest wall.
DAMPING OF SOUND ON THE CHEST SURFACE

In 1944, Levine and Likoff\(^8\) pointed out "that a murmur is transmitted in all directions from the point of maximum intensity, and that once the sound strikes bone it is best transmitted through contiguous bony structures." The present results show that this is true for frequencies above 100 cycles/sec. It has also been shown\(^6,8\) that in most human subjects the velocity of conduction is much higher on the sternum than elsewhere on the precordium. For this reason, it will be difficult to determine the exact location of the point of maximum intensity, the secondary source, if this point is located on the sternum.

The damping of heart sounds during transmission from their place of origin to the surface of the body consists of the damping reported in this paper and of the attenuation of the sounds during their transmission from the heart to the chest wall. The attenuation of sound during its transmission from the cavities of the heart to the surface of the chest has recently been measured in dogs,\(^8\) but these measurements included the attenuation occurring at the interface between the blood in the ventricle and the ventricular wall. Whether normal heart sounds and murmurs have to cross this interface is not certain. The damping and the mode of conduction of the heart sounds in the heart itself remain to be explored in order to complete the description of the paths followed by the heart sounds travelling from their place of origin to the surface of the body.

Summary

The damping of sound during its transmission over the chest wall was measured in humans in order to establish whether the heart sounds spread in two-dimensions over the chest wall from their auscultatory areas, or in three-dimensions directly from their origins deep in the body.

The damping of frequencies from 50 to 400 cycles/sec in soft tissues and ribs can be predicted by an equation which consists of a geometrical term and a term due to viscous damping.

The term which represents the viscous damping in the soft tissues and ribs of the chest wall is proportional to the square root of the frequency.

The value of the geometrical term suggested that the intensity of the sounds was inversely proportional to the distance travelled, rather than inversely proportional to the square of the distance travelled. The former relationship would apply if the sound travels in a two-dimensional plane of material rather than in a three-dimensional volume. This is consistent with our earlier finding that the heart sounds travel from the heart to their auscultatory areas on the chest and from there over the chest surface.

For frequencies under 100 cycles/sec, the chest wall appears to be homogeneous. For frequencies above 100 cycles/sec, the damping is much less for transmission over the sternum than for transmission elsewhere on the precordium.

Appendix

If the observed relationship\(^5,14\) between the velocity of conduction and the frequency is given by:

\[ v = k (f)^{1/2} \]  

where \(v\) is the (phase) velocity in cm sec\(^{-1}\), and \(k\) is a constant whose value can be calculated to be about 150 (cm sec\(^{-1/2}\)); and if the relation between velocity, wave length, and frequency\(^5\) is given by:

\[ v = \lambda f \]  

where \(\lambda\) is the wave length (cm) it follows that:

\[ \lambda (f)^{1/2} = k \]  

In equation 2, the geometrical term is dropped as it has already been accounted for. If both sides of equation 2 are divided by 12.5 (the distance in centimeters between the reference point through which the first contour line was drawn and the farthest corner of the field), the equation becomes:

\[ D = c (f)^{1/2} \]  

where \(D\) is the damping per centimeter (db cm\(^{-1}\)) and \(c\) is a constant of value 2.25/12.5 = 0.18 (db cm\(^{-1}\) sec\(^{-1/2}\)). The damping per wavelength which we call \(d\) is then:

\[ d = \lambda c (f)^{1/2} \]  

and it follows from equations 5 and 7 that:

\[ d = \lambda c k \]  

which means that \(d\), the damping per wavelength,
is constant in this medium and has a value of 0.18 \times 150 = 27 \text{ decibels per wavelength}. Since the standard error of the value 2.20 in equation 2 is 0.375 (i.e., about 17\%), the standard error of the damping per wavelength is 4.6 \text{ decibels}.

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References

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