Sound in medicine

General properties of sound

A sound wave is a mechanical disturbance in a gas, liquid, or solid that travels outward from the source with some definite velocity. We can use a loudspeaker vibrating back and forth in air at a frequency f to demonstrate the behavior of sound. The vibrations cause local increases and decreases in pressure relative to atmospheric pressure (Fig. 1). These pressure increases, called compressions, and decreases, called rarefactions, spread outward as a longitudinal wave, that is, a wave in which the pressure changes occur in the same direction the wave travels. The compressions and rarefactions can also be described by density changes and by displacement of the atoms and molecules from their equilibrium positions.

The relationship between the frequency of vibration f of the sound wave the wavelength λ, and the velocity ν of the sound wave is

$$\nu = \lambda f$$

For example, for a sound wave with a frequency of 1000 Hz, ν=344 m/sec in air at 20 °C and λ= 0.344 m.

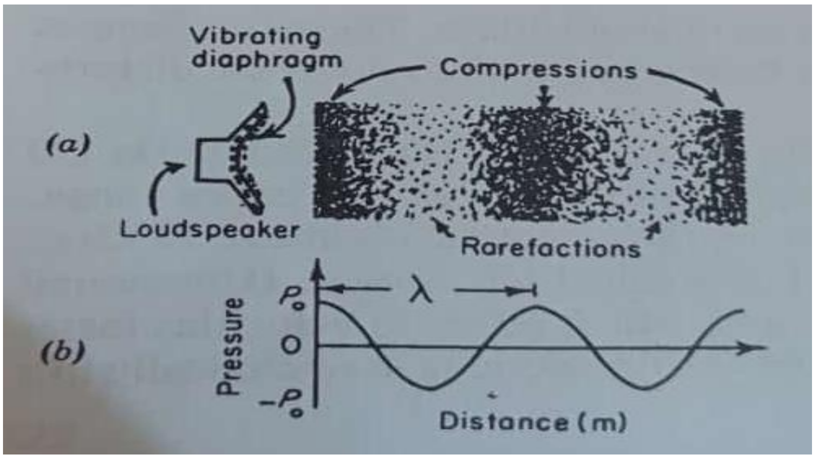

Figure 1

Table1 Values of ρ, ν, and Z for various substances at clinical ultrasound frequencies

	ρ (kg/m^3)	ν (m/sec)	Z (kg/m^2 · sec)
Air	1.29	3.31×10^2	430
Water	1.00×10^3	14.8×10^2	1.48×10^6
Brain	1.02×10^3	15.3×10^2	1.56×10^6
Muscle	1.04×10^3	15.8×10^2	1.64×10^6
Fat	0.92×10^3	14.5×10^2	1.33×10^6
Bone	1.9×10^3	40.4×10^2	7.68×10^6

Energy is carried by the wave as potential and kinetic energy. The intensity I of a sound wave is the energy passing through 1 m^2/sec, or watts per square meter. For a plane wave I is given by

$$I = \frac{1}{2}\rho v A^2 (2\pi f)^2 = \frac{1}{2} Z (A\omega)^2 \dots\dots\dots\dots (1)$$

Where ρ is the density of the medium; ν is the velocity of sound; f is the frequency; ω is the angular frequency, which equals $2\pi f$; A is the maximum displacement amplitude of the atoms or molecules from the equilibrium position; and Z, which equals ρν, is the acoustic impedance. Some typical values of ρ, ν, and Z are given in table 1. The intensity can also be expressed as

$$I = \frac{P_o^2}{2Z} \dots\dots\dots\dots\dots (2)$$

Where P_O is the maximum change in pressure.

When a sound wave hits the body, part of the wave is reflected and part is transmitted into the body (Fig. 2). The ratio of the reflected pressure amplitude R to the incident pressure amplitude A_O depends on the acoustic impedances of the two media, Z_1 and Z_2. The relationship is

$$\frac{R}{A_o} = \frac{Z_2 - Z_1}{Z_1 + Z_2} \dots\dots\dots\dots.. (3)$$

For a sound wave in air hitting the body, Z_1 is the acoustic impedance of air and Z_2 is the acoustic impedance of tissue. Note that if Z_1=Z_2, there is no reflected wave and transmission to the second medium is complete. Also, if $Z_2 < Z_1$, the sign change indicates a phase change of the reflected wave.

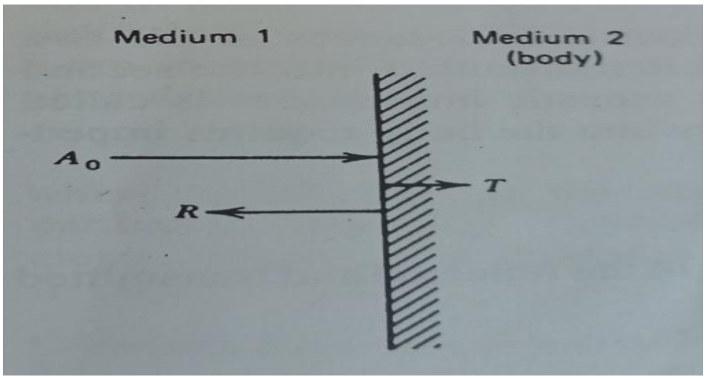

Figure 2

The ratio of the transmitted pressure amplitude T to the incident wave amplitude A_o is

$$\frac{T}{A_o} = \frac{2Z_2}{Z_1 + Z_2} \quad \ldots\ldots\ldots\ldots\ldots (4)$$

In our discussion of the reflection of a sound wave we assumed that the wave was perpendicular to the surface. Thus the transmitted wave went straight in and the reflected wave went straight back. How do the reflected and transmitted sound waves behave when a wave hits at an angle θ_i to a boundary between two media (Fig. 3)?

The geometric laws involving the reflection and refraction (bending) are the same as for light. This means that θ incident = θ reflected, or $\theta_i = \theta_r$. The angle of the refracted sound wave θ_2 is determined by the velocities of sound in the two media v_1 and v_2 from the equation

$$\frac{\sin\theta_i}{v_1} = \frac{\sin\theta_2}{v_2}$$

Because sound can be refracted, acoustic lenses can be constructed to focus sound waves.

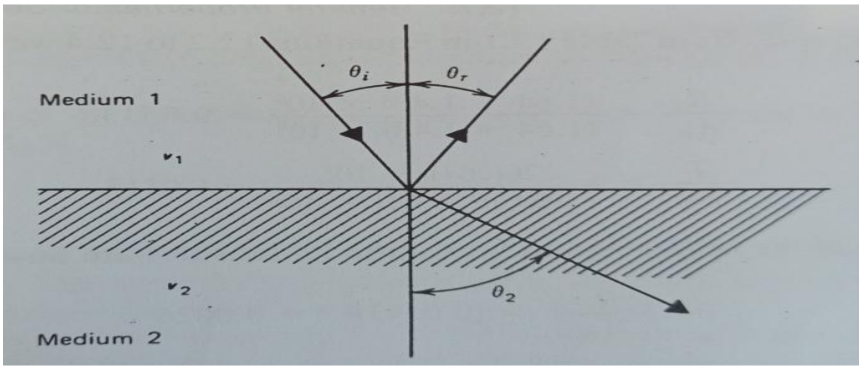

Figure 3

When s sound wave passes through tissue, there is some loss of energy due to frictional effects. The absorption of energy in the tissue causes a reduction in the amplitude of the sound wave. The amplitude A at a depth x cm in a medium is related to the initial amplitude A_o (x=0) by the exponential equation

$$A = A_o e^{-\alpha x}$$

Where α, in cm^{-1} , is the absorption coefficient for the medium at a particular frequency. Table 2 gives some typical absorption coefficients.

Table 2 Absorption coefficients and half-value thicknesses for various substances.

Material	Frequency (MHz)	α (cm^{-1})	Half-Value Thickness (cm)[a]
Muscle	1	0.13	2.7
Fat	0.8	0.05	6.9
Brain (ave)	1	0.11	3.2
Bone (human skull)	0.6	0.4	0.95
	0.8	0.9	0.34
	1.2	1.7	0.21
	1.6	3.2	0.11
	1.8	4.2	0.08
	2.25	5.3	0.06
	3.5	7.8	0.045
Water	1	2.5×10^{-4}	1.4×10^{3}

Since the intensity is proportional to the square of the amplitude, its dependence with depth is

$$I = I_o e^{-2\alpha x} \dots\dots\dots\dots\dots (5)$$

Where I_0 is the incident intensity at x=0 and I is the intensity at a depth x in the absorber. Since the absorption coefficient in equation 5 is 2α, the intensity decreases more rapidly than the amplitude with depth.

The half-value thickness (HVT) is the tissue thickness needed to decrease I_0 to $I_0/2$. Table 2 gives typical HVTs for different tissues. Note the high absorption in the human skull and that the absorption increases as the frequency of the sound increases. This increasing absorption with frequency also occurs for other body tissues and limits the maximum frequencies that can be used clinically (Fig. 4).

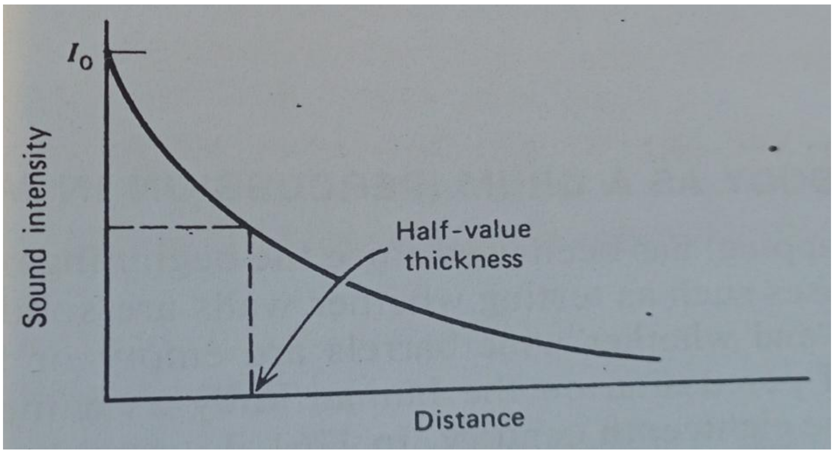

Figure 4

In addition to the absorption of sound, the spreading out, or divergence, of sound causes the intensity to decrease. If the sound is from a small source (point source) the divergence causes the intensity to decrease according to the inverse square law. That is, I is proportional to $1/r^2$ where r is the distance from the source to the measuring point.

The stethoscope

The main parts of a modern stethoscope are bell, which is either open or closed by a thin diaphragm, the tubing, and the earpieces (Fig. 5) .

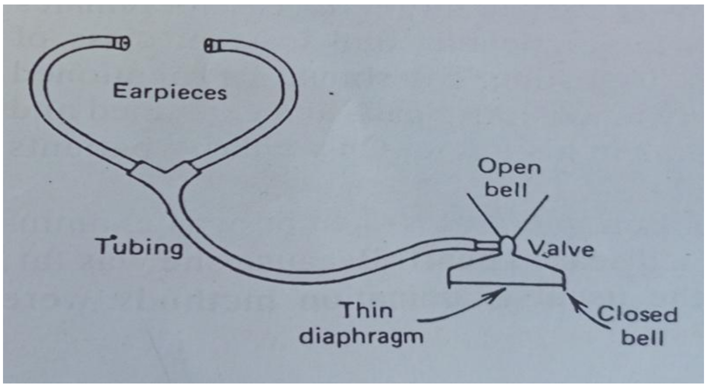

Figure 5

The open bell is an impedance matcher between the skin and the air and accumulates sounds from the contacted area. The skin under the open bell behaves like a diaphragm. The skin diaphragm has a natural resonant frequency at which it most effectively transmits sounds; the factors controlling the resonant frequency are similar to those controlling the frequency of a stretched vibrating wire. The tighter the skin in pulled, the higher its resonant frequency. The larger the bell diameter, the lower the skin's resonant frequency. Thus it is possible to enhance the sound range of interest by changing the bell size and vary the pressure of the bell against the skin and thus the skin tension. A low-frequency heart murmur will appear to go away if the stethoscope is pressed hard against the skin!

A closed bell is merely a bell with a diaphragm of known resonant frequency, usually high, that tunes out low-frequency sounds. Its resonant frequency is controlled by the same factors that control the frequency of the open bell pressed against the skin. The closed-bell stethoscope is primarily used for listening to lung sounds, which are of higher frequency than heart sounds. Figure 6 shows the typical frequency ranges of heart and lung sounds.

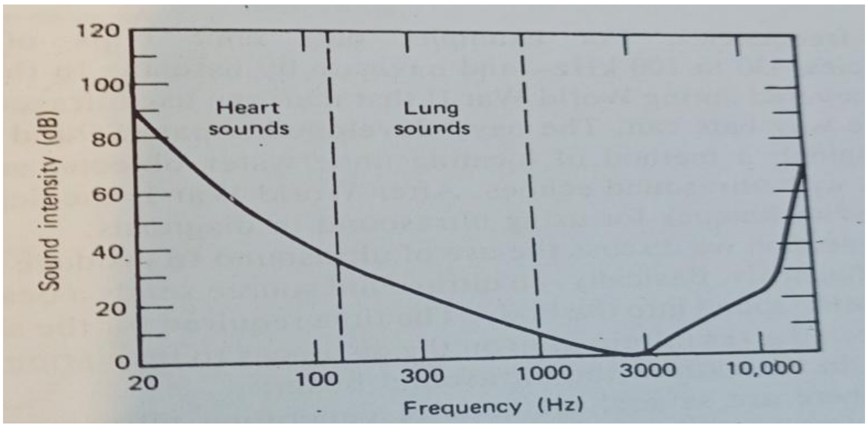

Figure 6

The volume of the tubes should also be small, and there should be little frictional loss of sound to the walls of the tubes. The small volume restriction suggests short, small diameter tubes, while the low-friction restriction suggests large diameter tubes. If the diameter of the tube is too small, frictional losses occur, and if it is too large, the moving air volume is too great; in both cases the efficiency is reduced. Below about 100 Hz tube length does not greatly affect the efficiency, but above this frequency the efficiency decreases as the tube is lengthened. At 200Hz 15dB is lost in changing from a tube 7.5 cm long to a tube 66 cm long. A compromise is a tube with a length of about 25 cm and a diameter of 0.3 cm.

The earpieces should fit snugly in the ear because air leaks reduce the sounds heard. The lower the frequency, the more significant the leak. Leaks also allow background noise to enter the ear. The earpieces are usually designed to follow the slightly forward slant of the ear canals.

Mechanism of hearing

The sense of hearing involves:

1. The mechanical system that stimulates the hair cells in the cochlea.
2. The sensors that produce the action potentials in the auditory nerves.
3. The auditory cortex, the part of the brain that decodes and interprets the signals from the auditory nerves (Fig. 7).

Deafness or hearing loss results if any of these parts malfunctions.

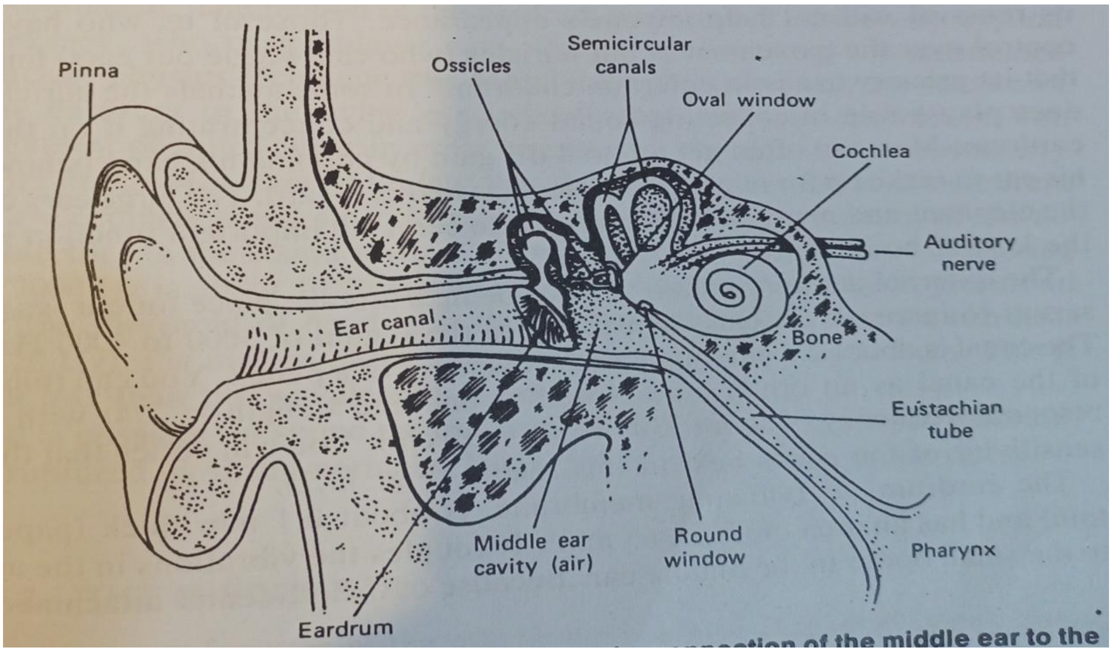

Figure 7