1 Anatomy and Physiology of Hearing, Hearing Impairment and Treatment

1.1 Introduction

The auditory system is a complex network that transduces pressure gradients caused by sound vibrations into neuroelectrical energy in the central nervous system. These neuroelectrical signals are then interpreted in the brain as, for instance, speech or music. Problems in the auditory system can lead to hearing difficulties or deafness.

Sound is an important source of information. Most face-to-face communication is by sound signals in the form of speech. However, persons who are deaf or hard-of-hearing may not be able to make use of sound signals for communicating effectively. Technology plays an important role in supporting the communication and information needs of deaf people and people who are hard-of-hearing. This includes hearing aids (Chapter 3), induction loop and infrared listening devices (Chapters 4 and 5), text and video telephones (Chapter 6), and visual or vibrating alarms and alerting devices (Chapter 7). Further research and development is still required in many of these technological areas, but especially those of the electro-vibratory and electro-tactile transmission of speech signals and speech–sign language text–signal language translation.

Understanding the basic principles of the auditory system and the basic causes of some of the main types of hearing loss can help engineers and technology experts to develop appropriate assistive devices, as well as to decide when assisted auditory, visual or tactile access to communication is more appropriate. This chapter aims to provide this basic understanding of hearing and hearing loss in order to serve as a foundation for understanding how to approach the development of assistive technology devices for deaf people and those who are hard-of-hearing.

1.1.1 Learning Objectives

The basic aim of this chapter is to give readers an understanding of the acoustics of sound and the functioning of the auditory system. Specific learning objectives include the following:

- basic understanding of the acoustics of sound, including how sound is propagated and how the propagation of sound relates to hearing;
- basic knowledge of the anatomy of the auditory system;
- some understanding of the functioning of each part of the ear;
- understanding how hearing loss is measured and various degrees and types of hearing loss;
- basic knowledge of the causes of the main types of hearing loss;
- basic knowledge of some primary medical and non-medical treatments for different types of hearing loss.

1.1.2 Overview of Hearing

Hearing is one of the five senses, along with vision, taste, smell, and touch. The ears receive sound and transmits it to the brain, where it is interpreted, so that speech, music, and other signals can be heard. Therefore, the auditory system requires a source of sound, a mechanism for receiving this sound, mechanisms for relaying sounds to the central nervous system, and pathways in the central nervous systems to deliver this sensory information to the brain where it can be interpreted, integrated, and stored. A cross-section of the ear, including the outer, the middle, and the inner ear with cochlea and auditory nerve, can be seen in Figure 1.1.

Most sounds are produced by vibration of air molecules from an oscillating source. In the case of speech, the vibrating source is the *vocal folds* or voice box in the throat or *larynx*. The ear can be divided into three main components: the outer, middle, and inner ear. The outer ear consists of the *pinna* or *auricle* and

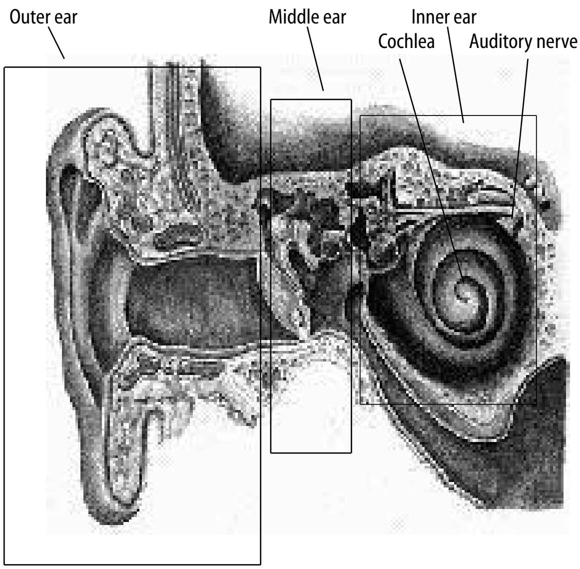


Figure 1.1 Cross-section of the ear, including outer, middle and inner ear with cochlea and auditory nerve (based on illustration courtesy of http://www.earaces.com/).

the ear canal or *external auditory meatus* (EAM). The eardrum or *tympanic membrane* is sometimes considered as part of the outer ear and sometimes as part of the middle ear.

The pinna generally protrudes to make it easier to capture sound waves. These captured waves are then funnelled by the pinna down the ear canal and strike the eardrum. The sound wave vibrations striking the eardrum make the membrane vibrate. The middle ear consists of three small bones or *ossicles*, the *malleus* (hammer), *incus* (anvil) and *stapes* (stirrup). Vibrations of the eardrum make the malleus, which is attached to it, move. This motion is transmitted to the other two ossicles. The three ossicles, or *ossicular chain*, transmit the eardrum vibrations to the end portion of the stapes, called the *footplate*, as it resembles the part of a stirrup into which the foot is placed when mounting a horse.

The middle ear is separated from the inner ear by a bony wall. The footplate fits into the *oval window*, an oval hole in this wall. The inner ear is divided into two sensory parts. The first part is called the *vestibular system* and is the sensory system of the inner ear involved with balance, motion, and feedback related to the body's position in space. It is *not* involved in hearing or auditory sensitivity. The auditory portion of the inner ear is called the *cochlea*. It is a fluid-filled portion of the temporal bone that houses the sensory receptor structures of the auditory system in its central portion, or *cochlear duct*. This duct can be thought of as a membranous canal in the fluid-filled cochlea. The auditory receptor cells are in the cochlear duct. They are called *hair cells*, as they have hair-like protrusions (*cilia*).

Motion of the footplate causes waves in the fluids of the cochlea. As the waves travel down the cochlea, the cochlear duct moves up and down. This movement leads to a bending of the cilia, causing the hair cells to release neurochemicals from their bases. The fibres or *neurons* of the auditory nerve, known as the eighth cranial nerve or the eighth nerve, are below the hair cells. These neurons receive the neurochemicals, giving rise to a neural impulse that travels along the fibres or *axons* of the eighth nerve. The cochlea, its internal structures, and the eighth nerve make up the auditory portion of the inner ear.

The auditory nerve connects the cochlea with the *brainstem*, a portion of the central nervous system above the spinal cord, but below the *cortex* or brain. In the brainstem, the auditory sensory information from the stimulation of the cochlea is transmitted as neuroelectrochemical activity through a succession of neurons to the auditory reception areas of the cortex. In the cortex, the nerve connections transmit the sound sensations to various parts of the brain, where they are interpreted, form mental images, and are stored for later use. The brainstem and cortical auditory pathways are known as the *central auditory nervous system* (CANS) or more simply as the auditory pathways.

1.1.3 The Auditory System in Engineering Terms

The signals of interest originate as sound pressure waves and are transformed into electrochemical nerve signals that are processed by the auditory brainstem and in the auditory cortex of the brain.

The ear can be considered as a signal-processing device that performs the following functions (Figure 1.2):

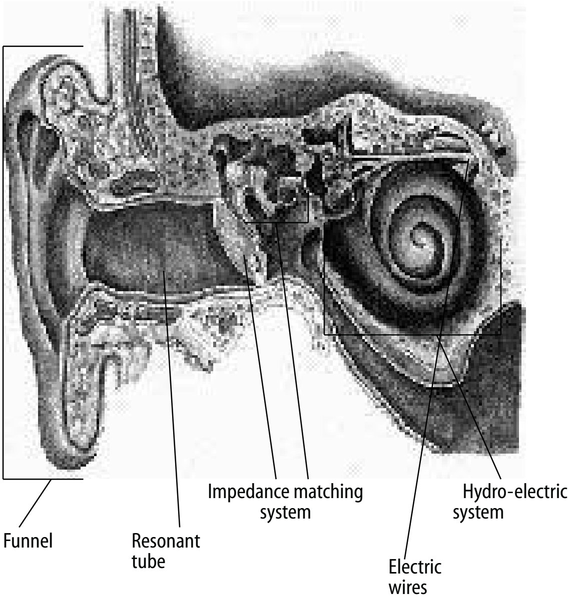


Figure 1.2 The auditory system in engineering terms (based on illustration courtesy of http://www.earaces.com/).

- transduction
- filtering
- amplification
- non-linear compression
- impedance matching
- spectral analysis.

Although this type of engineering system is useful, it is also important to recognise the difference between human and electromechanical systems. Other factors, including processing in the brain, individual perceptions, and emotions, also affect hearing.

1.2 Acoustics of Hearing

Hearing begins with the propagation of a sound wave. Therefore, to understand hearing and hearing loss, it is necessary to understand how sound is generated and how it travels from its source to the ear. Sound is produced by a vibrating or oscillating body. It then travels as *longitudinal waves* through a medium, usually air, to the ear. It can also travel through other mediums, such as liquids and solids.

The vibrating body transmits the vibration to the molecules of air in contact with it, making them vibrate. This motion is resisted by the *frictional resistance* of air, which converts some of the kinetic energy of motion into heat and

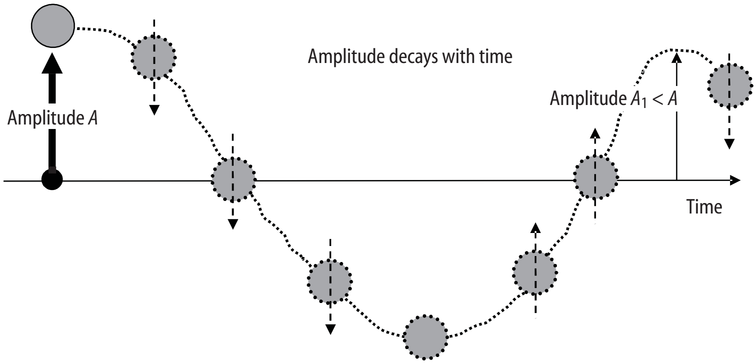


Figure 1.3 Oscillatory motion of air molecule and the effect of frictional resistance.

reduces the amplitude of the oscillation until the air molecules stop moving. However, the vibration is communicated to other molecules and will travel through the air until it encounters an object that acts as an opposing force. Objects that are elastic, such as the eardrum, will start oscillating due to the force of the air molecules striking them.

The graph in Figure 1.3 shows displacement from the rest position against time. The *amplitude* of a particular wave is the distance between any wave peak (*e.g.* amplitudes A and A_1 in Figure 1.3) and the position of rest on the horizontal axis. The effect of frictional resistance is to reduce the amplitude as time progresses.

The longitudinal sound wave resulting from the vibration of an object being communicated to and travelling through the air molecules is illustrated in Figure 1.4. The difference between the vibration of each air molecule about a point of rest and the wave that moves through the air molecules should be noted. The figure illustrates points of *compression*, where the air molecules are clumped together due to the motion, and points of *rarefaction*, where the molecules are spread out.

Figure 1.5 shows the sound wave travelling from its source as a series of concentric circles. Each circle represents points of compression and the spaces between the circles represent points of rarefaction.

Important features of a sound wave include amplitude, frequency and phase.

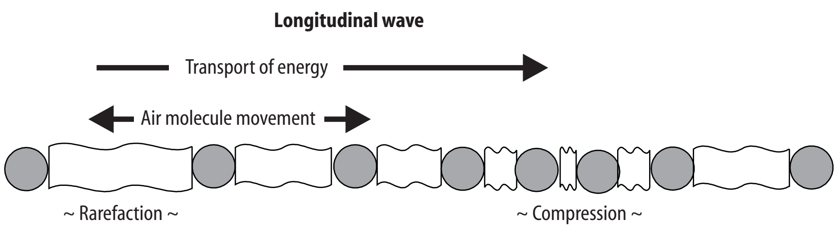


Figure 1.4 Longitudinal sound wave.

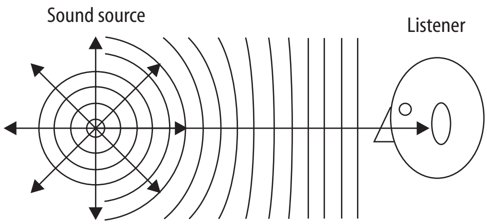


Figure 1.5 Sound spreading out from a source (by kind courtesy of http://interface.cipic.ucdavis.edu/CIL_tutorial/3D_phys/sines.htm).

1.2.1 Amplitude

The amplitude of a sound wave is the maximum displacement of an air molecule from its rest position. Since it is produced by a vibrating body making contact with air molecules and applying a force to them, sound amplitude is measured as the *sound pressure level* (SPL), as pressure is equal to force divided by area, in this case the force from the vibrating body over the area into which it comes in contact with or the area of the eardrum when this vibration is transmitted to the eardrum.

The smallest SPL at which sound can be perceived is taken as 20 μPa (micropascals). This gives the first point (zero) of the amplitude scale. The amplitude of sound measured is generally measured relative to the *peak amplitude*, *i.e.* the SPL measured in micropascals at the peak (see root-mean-square below). Sound pressure can also be measured at other points than peaks on a sound wave.

It can also be shown that the sound wave moves with *simple harmonic motion* with distance from rest or amplitude given by

$$y = A\sin 2\pi ft = A\sin\omega t$$

where A is the peak amplitude and ω is a measure of angular velocity, given by $\omega = 2\pi f$ with f the frequency of the wave. Since the amplitude of the signal y is measured as a sine function, the sound wave can be considered as a *sine wave*. The above sine wave equation can be obtained by considering the wave motion of the sound wave as *uniform circular motion*, in which the motion of any point P on the sound wave can be seen to be analogous to motion around the circumference of a circle, as shown in Figure 1.6.

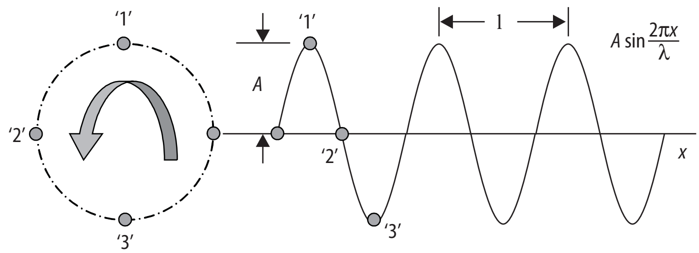


Figure 1.6 Circular motion.

On this circle, the points at rest are the two points on the circle circumference on the *x* axis and the points of maximum displacement are the two points on the circle circumference on the *y* axis.

Sound amplitude is generally measured using the *root-mean-square* (r.m.s.) amplitude, which is denoted by A_{rms}. In the case of a sine wave, the r.m.s. value is 0.707 times the peak amplitude or 70.7% of the peak amplitude. Thus, $A_{rms} = 0.707A$, where A is the peak amplitude.

1.2.2 Phase

As already seen above, sound waves can be represented by sine waves. The *phase* of a sine or sound wave indicates at what point in the cycle the sound wave starts. For instance, a sound wave with phase of 90° starts with its maximum amplitude rather than at rest and, therefore, is equivalent to a cosine wave (see Figure 1.7(a) and (b)). Phase angle varies from 0 to 360°. It is also useful to compare the phase angles of different sine waves to obtain the relative phase, as shown in Figure 1.7, where the three sine waves shown have relative phases of 0°, 90° and 180°. This factor becomes important when considering that sound in the environment is made from various sine waves that may have differing phases. The interaction of phase becomes important when, for

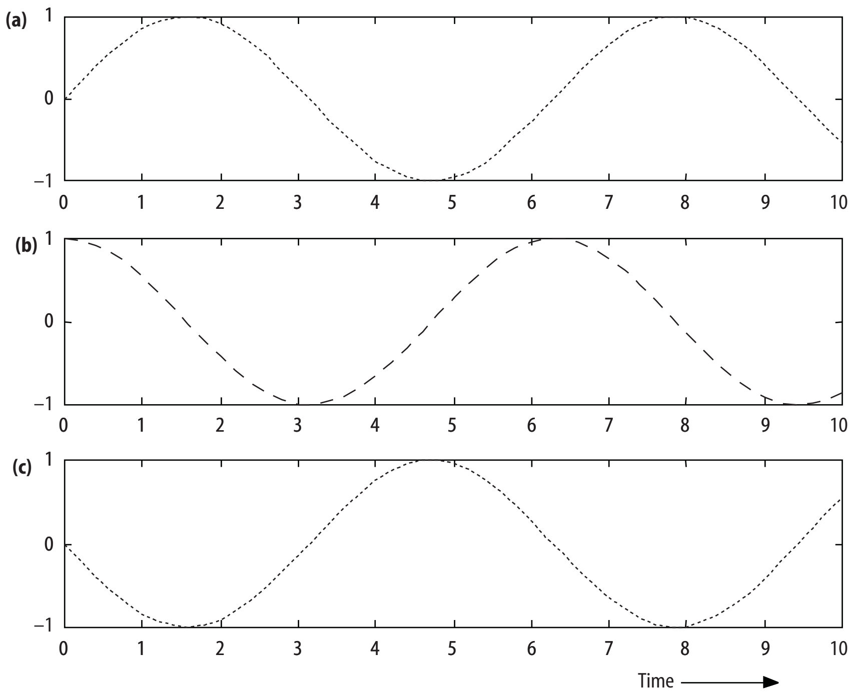


Figure 1.7 The relative phase of three sinusoidal waves: **(a)** sine wave with no phase shift; **(b)** sine wave with 90° phase shift; **(c)** sine wave with 180° phase shift.

example, two sounds of the same frequency and intensity are 180° out of phase. In such a case, the sounds cancel each other out, leading to no sound being perceived (consider adding the two sine waves in Figure 1.7(a) and (c) together). This is one method for eliminating unwanted sound.

1.2.3 Frequency and Period

Frequency is the number of cycles or complete oscillations per second. A cycle is an oscillation of an air molecule from rest through the points of maximum displacement (A and B) and back to the initial point of rest. Frequency is generally measured in hertz or cycles per second. In terms of circular motion, a cycle is equivalent to moving round the circle once or going through 360° or 2π radians. Therefore, frequency is also sometimes measured as angular frequency in radians per second.

Period is the length of time taken to complete one cycle. Therefore, it is the inverse of the frequency. Thus, a sound with a frequency of 1000 Hz has a period of 1/1000 s or 1 ms.

1.2.4 Sound Intensity and the Decibel Scale

The amplitude or SPL of a sound is also related to the *intensity* of a sound. Intensity is the measure of energy used per unit of time per unit of area. Since the area of molecular movement for sound waves is fairly small, it is usually measured in centimetres squared (cm^2) and time is measured in units of seconds. Thus, intensity is measured as joules/second/cm^2 or equivalently as watts/cm^2. Sound intensity is used in acoustics, for example, when measuring sound from a loudspeaker. However, in hearing it is the pressure of sound striking the eardrum rather than the sound intensity that is significant.

Studies of sound perception have shown that sound intensity is related to the ratio of the measured pressure P_{m} for the sound under investigation to the pressure P_{r} for the softest sound that can be heard (called the reference pressure). This reference pressure is $P_r = 20$ μPa. Thus, sound intensity is perceived as the ratio $(P_m/P_r)^2$. It has also been shown experimentally that multiplying the sound pressure in micropascals by a factor of ten is required to give a perceived doubling of loudness. For instance, a sound of 200 μPa is twice as loud as one of 20 μPa, and a sound of 2000 μPa is four times as loud as one of 20 μPa.

This finding suggests the use of a scale based on logarithms to the base ten would be convenient. Such a scale, called the bel (B) scale, is used in sound and acoustics and is named after the pioneering engineer in this field, Alexander Graham Bell. However, when measurements of sound are made, using bels gives a rather small range and also gives many sound pressures with values of one decimal place, such as 3.5 or 6.4 B. This is not so convenient, so the decibel (dB) is generally used. A bel is equal to 10 dB, and 6.4 B would become 64 dB.

The SPL can be obtained from measurements of the sound pressure P_{m} of a particular sound as

$$\text{Sound Pressure Level} = 10\log_{10}\left(\frac{P_m}{P_r}\right)^2 \text{ dB SPL}$$

$$= 20\log_{10}\left(\frac{P_m}{P_r}\right)\text{dB SPL}$$

In decibels, the softest sound has a value of

$$20\log_{10}\left(\frac{P_r}{P_r}\right) = 20\log_{10} 1 = 0 \text{ dB SPL}$$

and the loudest sound that can be experienced at the threshold of pain is 140 dB SPL. Thus dB SPL is measured with respect to the sound reference pressure, $P_r = 20$ μPa and this is a very useful measure of sound range.

1.2.5 Simple and Complex Sounds

A *simple sound* has a single frequency regardless of amplitude or SPL. Thus, 1000 Hz, 250 Hz, and 12,500 Hz are all simple sounds. The term *pure tone* is sometimes used to denote a sound at a single frequency. Pure tones are used in measuring hearing and hearing loss (see Chapter 2). A simple sound is produced by a single vibrating mass (sound source) producing an audible sound (of 0 dB SPL or greater); the sound is of a single frequency. However, most vibrating sources are more than just a single mass. For example, the vocal folds that produce voice are housed in a structure (the throat or *pharynx*) that is itself able to vibrate. The initial sound from the vocal folds then causes oscillation in the vocal tract of the pharynx. The oscillation of other masses or structures due to an original sound is called *resonance* and the structure is said to *resonate*. Therefore, most complex sounds, such as speech, are due to an initial sound mixed with resonated sounds.

A *complex sound* consists of a base or *fundamental* frequency plus *harmonics*, *i.e.* multiples of the fundamental frequency. For example, a complex sound with fundamental frequency of 100 Hz could also have harmonics at 200, 300, 400, and 500 Hz. The harmonics are often denoted f_0, f_1, f_2 and so on, with f_0 the first harmonic or fundamental frequency, f_1 the first *overtone* or second harmonic, and so on. However, a complex sound does not always have its entire harmonics. For instance, a complex sound with five harmonics could consist of the first five harmonics or the fundamental plus odd harmonics, *e.g.* 100, 300, 500, and 700 Hz. Speech is produced by this fundamental plus odd harmonics resonance pattern and, therefore, the ability to hear complex sounds rather than only pure tones is important for understanding speech.

In the case of speech, the vocal tract is a tube that can be thought of as a resonant tube. The initial sound produced by the vocal folds is called the *fundamental frequency of voice* (for the given person). The resonance characteristics of the vocal tract determine the fundamental plus odd harmonics characteristics of speech.

Resonance is an important factor in speech and hearing. In addition to speech resulting from sound resonating within the vocal tract, the ear, itself, is a resonator. This resonance affects the ability to hear. Damage to the ear or using a hearing aid can change the resonant characteristics of the auditory system.

1.2.6 Spectral Analysis of Complex Sounds

Resonating systems produce sounds at two or more different frequencies. Complex sounds can be analysed using *spectral analysers* or *spectrograms* that carry out Fourier analyses of the sound. In the case of speech, and many other sounds that change rapidly over time, *fast Fourier transformation* (FFT) analysis is used.

When a spectral analyser completes an FFT, it provides a display of the results in numeric or data format or in graphical form. In hearing measurement, a graphical representation called a spectrogram is generally used. The spectrogram displays graphs of the amplitude (generally in dB SPL) along the y-axis against frequency (in hertz) on the x-axis. This information can be represented in two ways.

One type of spectrogram shows discrete frequency and amplitude information as a series of lines or bars, like a bar graph. A line is drawn for each frequency for which the intensity is greater than 0 dB SPL. This type of graph is sometimes called a *line display*. Figure 1.8 shows the line display for four harmonics of complex sound with a fundamental frequency of 50 Hz.

The most commonly used spectrogram in the field of hearing is called a *wave envelope*, as an envelope is produced by drawing lines to connect the peaks or tops of each line in the line display. There may also be, but are not always, lines below the envelope. Figure 1.9 shows the wave envelope for the complex sound in Figure 1.8.

1.2.7 Filtering Sound

Another important function that takes place in the auditory system is *filtering*. The inner ear can be considered, in part, as a series of band-pass filters that

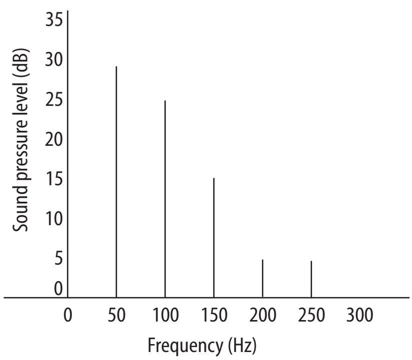


Figure 1.8 Line display spectrogram.

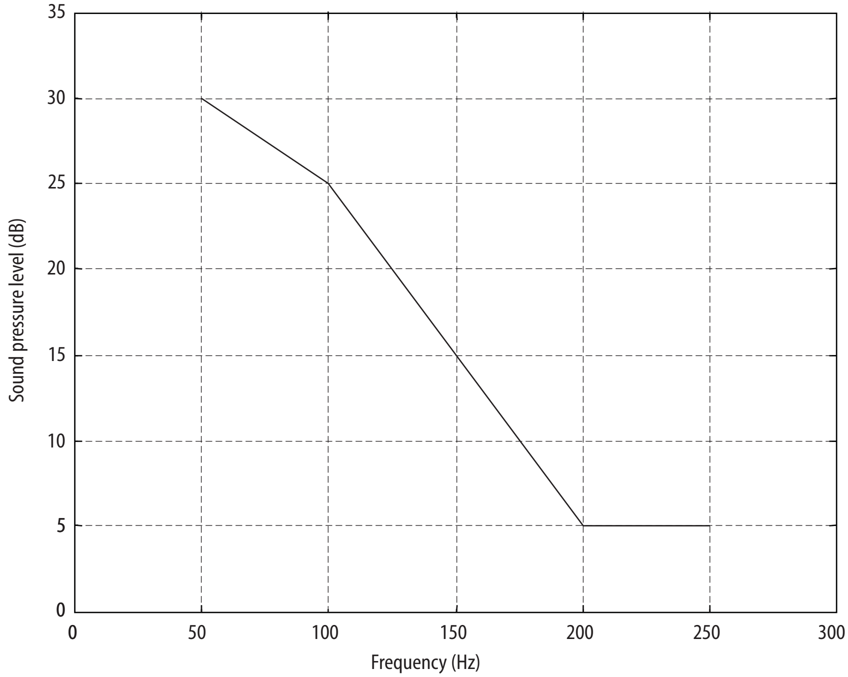


Figure 1.9 Wave envelope.

extract information from complex sounds. Filtering affects the spectral composition of a signal by reducing some frequencies in intensity and filtering out other frequencies. For instance, if an input sound having harmonics at the frequencies 50, 100, 150, 200, 250, and 300 Hz is passed through a system and the output sound has frequency components at 100, 150, 200, and 250 Hz, then the system has filtered out the harmonics at 50 and 300 Hz.

The filter *transfer function* describes the effect of a filter on an input signal, such as a sound signal. It is generally expressed as a rational function of frequency, as it determines the effect of the filter on frequency in the input signal. A typical filter transfer function could have the formula

$$G(j\omega) = \frac{K}{j\tau\omega + 1} = \frac{Y(j\omega)}{U(j\omega)}$$

The transfer function gives the ratio of the system output $Y(j\omega)$, as a function of frequency, to the input $U(j\omega)$, as a function of frequency. Evaluating the transfer function at a particular frequency gives a *multiplicative* effect on that frequency component. For instance, if the transfer function has an absolute gain of 0.7 at the frequency of 1000 Hz, then any signal passing through the filter will have its component at that frequency multiplied by the gain factor of 0.7, or its input dB amplitude reduced by $20\log_{10} 0.7 \approx -3$ dB. The signal amplitude reduction or attenuation occurs because the absolute gain factor is less than unity. Similarly, if the transfer function has an absolute gain of 0.3 at the frequency of 2000 Hz, then the frequency component at 2000 Hz in the incoming signal will leave the filter with its 2000 Hz component multiplied by the gain factor of 0.3, or its dB amplitude reduced by $20\log_{10} 0.3 \approx -10.5\,\text{dB}$. Again, the signal amplitude reduction or attenuation occurs because the gain factor is less than unity. The formula applied is given by

$$\text{Output amplitude} = [\text{Gain value}] \times \text{Input amplitude}$$

In dB or logarithmic form this is

$$[\text{Output amplitude}]\ \text{dB} = 20\log_{10}[\text{Gain value}]\ \text{dB} + [\text{Input amplitude}]\ \text{dB}$$

Thus if the absolute gain value is less than unity, then $20\log_{10}[\text{Gain value}]$ dB will be a negative dB value and a dB reduction in dB input signal amplitude occurs. If the absolute gain value had been greater than unity, then the output amplitude would be greater than the input amplitude and signal *amplification* will occur. In this case, the quantity $20\log_{10}[\text{Gain value}]$ dB will be a *positive* dB value and a dB addition to the dB input signal amplitude occurs.

In some cases the filter transfer function will be defined by the effect on different frequencies, *i.e.* a table of the filter reductions in dB at different frequencies, rather than as a mathematical expression. The system transfer function can be plotted on a graph, called a *filter curve*.

Example

Consider a complex sound consisting of the frequencies 100, 200, 300, 400, 500, 600, and 700 Hz, all at 40 dB SPL. The sound enters the system with each of the frequencies at 40 dB SPL. The output sound levels for the different harmonics are as follows:

100 Hz: 10.4 dB SPL
200 Hz: 14.0 dB SPL
300 Hz: 20.0 dB SPL
400 Hz: 40 dB SPL
500 Hz: 20.0 dB SPL
600 Hz: 14.0 dB SPL
700 Hz: 10.4 dB SPL

The amount of filtering at each frequency can be calculated to give the transfer function as follows:

100 Hz: $40 - 10.4 = 29.6$ dB SPL of filtering
200 Hz: $40 - 14.0 = 26.0$ dB SPL of filtering
300 Hz: $40 - 20.0 = 20.0$ dB SPL of filtering
400 Hz: $40 - 40 = 0$ dB SPL of filtering
500 Hz: $40 - 20.0 = 20.0$ dB SPL of filtering
600 Hz: $40 - 14.0 = 26.0$ dB SPL of filtering
700 Hz: $40 - 10.4 = 29.6$ dB SPL of filtering

The filter curve for this system is shown in Figure 1.10. It is a curve that is symmetric about the frequency 400 Hz, at which no filtering occurs.

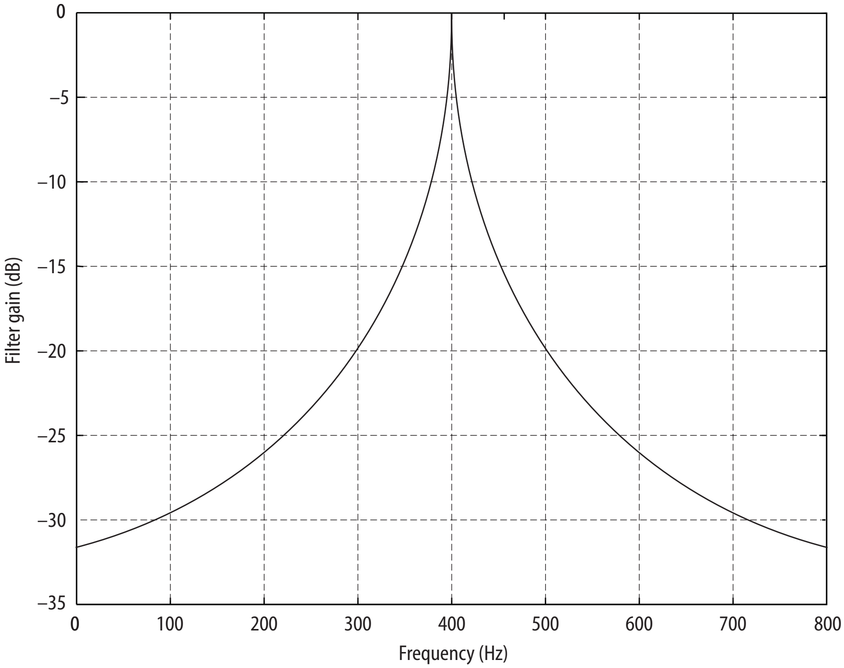


Figure 1.10 Filter curve.

Important filter characteristics include the upper and lower cut-off frequencies, the centre frequency, and the filter range, bandwidth or filter band. The *centre frequency* of a filter is the frequency in the middle of the range of frequencies for which no, or minimal, filtering occurs. It is generally assumed that a filter lets through frequencies where the amplitude is reduced by less than or equal to 3 dB and filters out frequencies that are reduced by more than 3 dB. This is known as the *3 dB down* point on the filter characteristic.

The *cut-off frequencies* are the frequencies at which filtering of −3 dB occurs, *i.e.* the outer limits of the frequencies let through. Some filters have both *upper* f_U and *lower* f_L cut-off frequencies, and others have either upper or lower cut-off frequencies but not both. The bandwidth or filter range is the difference between the upper and lower cut-off frequencies, namely, $f_U - f_L$ and the *frequency response* the range between the upper and lower cut-off frequencies. A filter can be specified in terms of its centre frequency f_c, and the cut-off frequencies that provide the limits of the frequency range of the filter.

Example

Consider a system with input 10 dB SPL at all frequencies and the following output levels:

100 Hz: 6 dB SPL
200 Hz: 7 dB SPL
300 Hz: 8 dB SPL
400 Hz: 9 dB SPL
500 Hz: 10 dB SPL
600 Hz: 9 dB SPL
700 Hz: 8 dB SPL
800 Hz: 7 dB SPL
900 Hz: 6 dB SPL

The centre frequency is 500 Hz with 10 dB SPL. Therefore, a reduction of 3 dB is 7 dB and the upper and lower cut-off frequencies are 200 Hz and 800 Hz.

Filters can also be described by their filter *band*, which is generally given by the number of octaves within the $f_L - f_U$ range. Harmonics are multiples of the fundamental and octaves involve doubling of the previous frequency. For example, for a fundamental frequency of 200 Hz, the harmonics are 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000 Hz, *etc*. and the octaves are: 200, 400, 800, 1600, 3200, 6400 Hz, *etc*.

For a filter with f_L = 500 Hz and f_U = 2000 Hz, the number of octaves from 500 to 2000 Hz is two. Thus, this filter has a *two-octave bandwidth*.

Sound is reduced or *attenuated* by a filter. The filter attenuation rate can be given in decibels per octave. A two-octave filter with 12 dB attenuation at one octave above or below the centre frequency has a 12 dB/octave attenuation rate.

Most filters can be categorised as low pass, band pass or high pass. *Band-pass filters* allow a particular band of frequencies to pass through the filter and have both upper and lower cut-off frequencies. *Low-pass filters* pass through all frequencies less than a certain frequency and, therefore, have only an upper cut-off frequency. *High-pass filters* pass through all frequencies above a certain frequency and have only a lower cut-off frequency.

1.3 Anatomy and Physiology of the Auditory System

1.3.1 Some Terminology Used in Describing Anatomical Structures

Before considering the specifics of the anatomical structures that receive and transmit sound and deliver it to the brain for processing, some of the terminology used in describing anatomical structures will be presented.

The term *frontal view* is used to describe a structure as seen from the front, whereas *dorsal view* refers to a back or rear perspective. *Lateral view* describes a perspective towards the side and *medial view* a perspective from the inside looking out; see Figure 1.11.

In addition to these four perspectives, anatomical structures are sometimes described in relation to each other. Structures on top are referred to as *superior*, whereas those underneath are referred to as *inferior*. Structures in back are *posterior* and those in front are *anterior*.

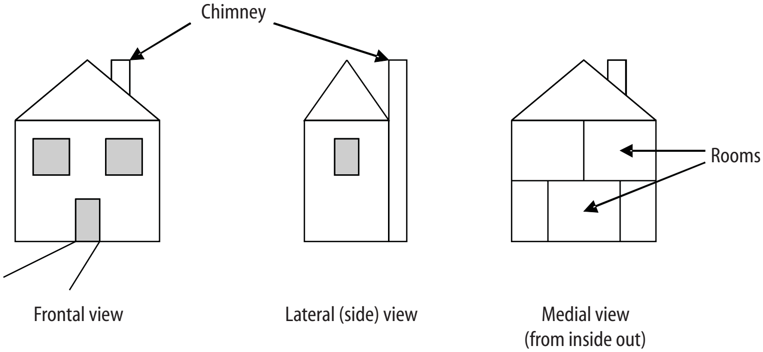


Figure 1.11 Anatomical perspectives.

The ear can be divided into three main parts: the outer, middle and inner ear (Figure 1.12). The anatomy and functions of these three parts will be discussed in the following sections.

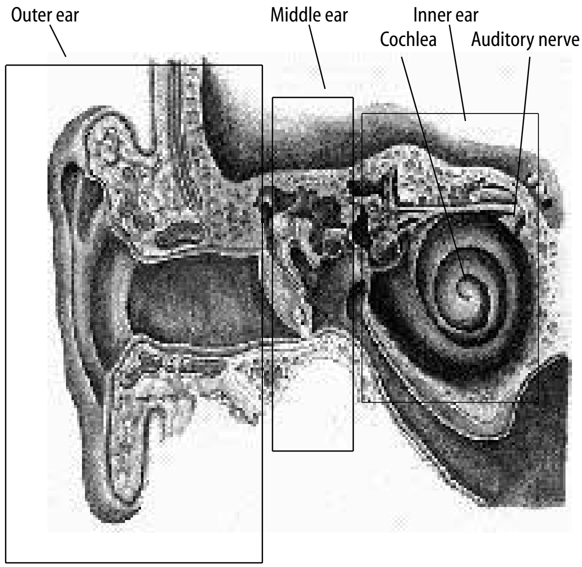


Figure 1.12 The structure of the ear (based on illustration courtesy of http://www.earaces.com/).

1.4 The Anatomy and Functions of the Outer-ear Structures

The outer ear consists of the pinna or the auricle and the ear canal or EAM that ends in the eardrum or tympanic membrane. The eardrum is sometimes considered as an outer-ear structure and sometimes as a middle-ear structure. It will be discussed here as part of the middle ear, as its functioning primarily involves the total physiology of the middle ear. The main function of the outer

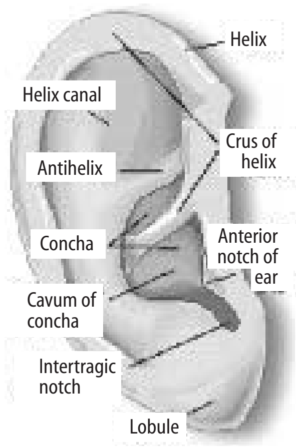


Figure 1.13 The pinna (based on an illustration courtesy of http://www.orlions.org/).

ear is to receive sound and funnel it down to the eardrum. Both the pinna and the EAM also act as a resonator of sound, and the EAM additionally filters out low-frequency sounds.

1.4.1 The Pinna

The *pinna* or the *auricle* receives sound from the environment and channels it into the auditory system. It is made of cartilage covered with skin and has a small inferior portion consisting of fatty tissue covered with skin.

Some animals, such as rabbits and dogs, can move their pinnae using the muscles attached to their pinnae to allow the structure to provide a directional factor and allow the pinna to pick up sounds from different directions. In humans, these muscles are dormant and do not function, although some people can "wiggle" their ears. Instead, movements of the neck twist the head, allowing the pinna to pick up sound from different directions.

Some of the main features of the pinna are shown in Figure 1.13. The superior portion is called the *helix*, which somewhat flaps over the *antihelix*. The helix comes down the posterior portion of the pinna to a soft part of the ear that consists of fatty tissue covered with skin having no cartilage. This is actually the *ear lobe* or *lobule*. In many animals, and in some people, the lobule is attached to the head and is not easily identifiable.

Superior and somewhat anterior to the lobule is a notch called the *tragal notch*. Superior to this is a part of the ear that often sticks out a bit, called the *tragus*. Opposite to this is the *antitragus*.

1.4.2 External Auditory Meatus

Between the tragus and antitragus is a recess that leads to the opening of the ear into the head. This recess is called the *concha* and it is the part of the pinna

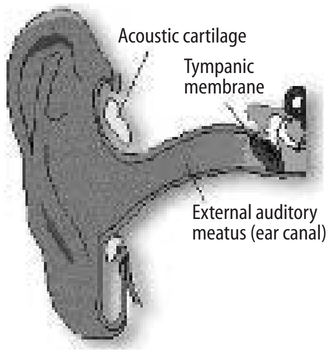


Figure 1.14 EAM (based on an illustration courtesy of http://www.orlions.org/).

that channels sound to the *ear canal* or *EAM*. The outermost portion of the EAM consists of cartilage covered with skin. As the EAM moves medially, the cartilage changes to bone, although it is still covered with skin, as shown in Figure 1.14.

The EAM ends, medially, at the eardrum or *tympanic membrane*, which, as noted above, some people refer to as a structure of the outer ear rather than the middle ear. Cells in the walls and floor of the EAM produce *cerumen* or earwax. Additionally, there are hairs in the lateral part of the EAM. Both the hairs and cerumen serve to trap foreign matter and objects that may enter the ear canal, helping to prevent them from getting down to the tympanic membrane, where they could possibly cause serious problems.

1.4.3 Functions of the Outer-ear Structures

The major function of the outer ear is to capture sound and funnel that sound down to the eardrum. The pinna sticks out to allow people to pick up sounds better from the front than from the back. This can be demonstrated by listening carefully to two sound sources from in front and behind, noting the volume or loudness of both sounds. When cupped hands are put around the pinna on both sides, the sound from in front should seem much louder than it was previously and the sound at the back quieter.

It is important to remember that sounds from in front are louder than those behind when considering a person wearing a hearing aid. With a behind-the-ear (BTE) or body-worn hearing aid, the sound is picked up from a microphone that is placed outside the region of the pinna. Thus, the localisation effects of the pinna are not available in these types of hearing aid and people often complain of interfering background sounds more when using BTE and body-worn hearing aids. A more complete discussion of hearing aids will be given in Chapter 3.

In addition to picking up sound, the pinna acts as a slight resonator of sound. The concha is recessed and forms a small cave-like structure, called the *cavum concha*. The cavum concha makes sound resonate slightly, but enough to enhance the loudness of sound entering the ear, especially from the front.

The final auditory function of the pinna, especially the concha, is to funnel the sound to the opening to the EAM, where the sound travels to the tympanic membrane. The EAM is a tube closed medially and open laterally. As tubes cause resonance, the EAM acts as an acoustic resonator. In humans, the resonant characteristics of the EAM are around 10 dB in the frequency range from 2500 to 5000 Hz. The peak is usually around 3000 Hz. Thus, higher frequencies of sound enter the EAM and are resonated by a factor of about +10 dB.

This EAM resonance is important for understanding speech. Consonants carry important linguistic information. For instance, consider the words "hat" and "cat". There is a considerable difference in meaning, but the only acoustic difference is the slight, high-frequency energy difference in the consonant sounds of "h" and "c" (represented as the speech sound or *phonemes* /h/ and /k/). Vowels contain a great deal of acoustic energy; this contrasts with the consonants, which have significantly less, especially the high-frequency consonants. Thus, the EAM helps to increase the energy in these high-frequency sounds by resonating these frequencies when they travel through the outer ear.

The other important concept to understand about the EAM tube is that it is open at its lateral end. This allows low-frequency sounds to be filtered out of the EAM. Again, this serves to enhance the energy for the higher frequencies. Therefore, the EAM functions as a high-pass filter.

This filtering factor becomes important in considering the effects of fitting a hearing aid. For most hearing-aid users, the hearing aid is fitted into the ear with an earmould, whether part of the hearing aid (as with in-the-ear and in-the-canal models) or separate from the hearing aid (as with BTE and body-aid models). Placing an earmould into the opening of the EAM removes the open-tube filtering effects of the ear canal and changes its resonant characteristics. Chapter 3 has a more detailed discussion of hearing aids and earmould effects.

1.5 The Anatomy and Functions of the Middle-ear Structures

The middle ear consists of three ossicles and the tympanic membrane, which can be considered as either part of the outer or middle ears. It will be discussed here as part of the middle ear, as its function has been shown to be integrally related to the middle-ear impedance matching.

1.5.1 The Tympanic Membrane

As its name implies, the tympanic membrane (Figure 1.15) is a membrane. The acoustic energy from the sound travelling down the EAM is translated into motion of the tympanic membrane. This motion is directly related to the compression and rarefaction motion of the air molecules travelling as the sound wave. Thus, when compression occurs, the tympanic membrane moves medially; and when rarefaction occurs, the tympanic membrane moves laterally. Thus, the tympanic membrane moves in-and-out or back-and-forth.

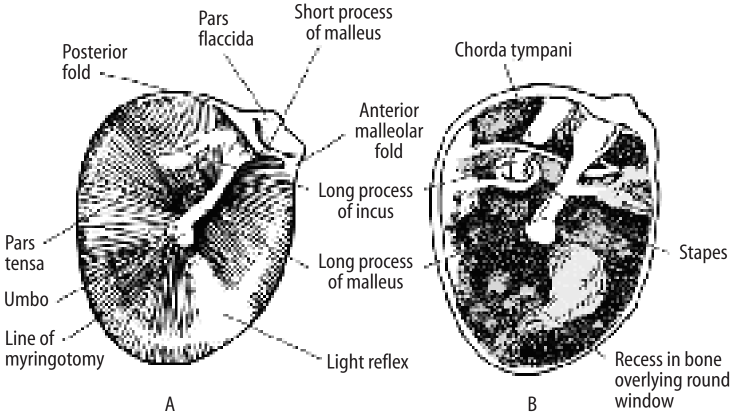


Figure 1.15 Tympanic membrane (by kind courtesy of http://www.merck.com/pubs/mmanual/figures/).

1.5.2 Middle-ear Ossicles

There are three small bones, or ossicles, in the middle ear, called the *malleus* (hammer), *incus* (anvil) and *stapes* (stirrup); see Figure 1.16. The malleus, or hammer, is attached to the tympanic membrane. Like the hammer from which it derives its name, the malleus has two parts, the head and the arm, called the *manubrium*.

The lateral end of the manubrium is attached to the centre, or *umbo*, of the tympanic membrane. Thus, movement or oscillation of the tympanic membrane is transmitted directly to the malleus. The malleus is also suspended from the bony walls of the middle ear at several points, so that it can move as the vibrations of the tympanic membrane are transmitted to it. Thus, as the tympanic membrane moves medially, the malleus does the same because of this direct vibration.

The head of the malleus is rounded like a mallet and is attached to the head of the incus, the next middle-ear ossicle, via ligaments (see Figure 1.16). The head of the incus is indented to form a *ball-in-socket* attachment. This type of

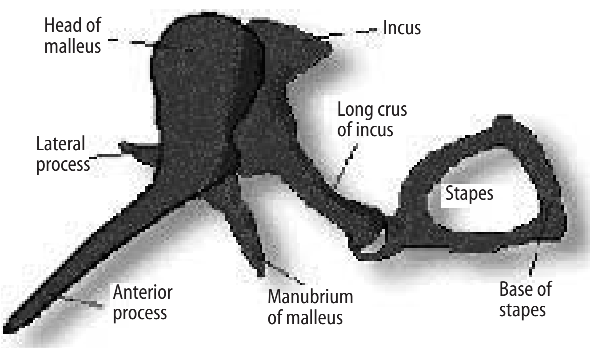


Figure 1.16 Malleus, incus and stapes (based on an illustration courtesy of http://www.orlions.org/).

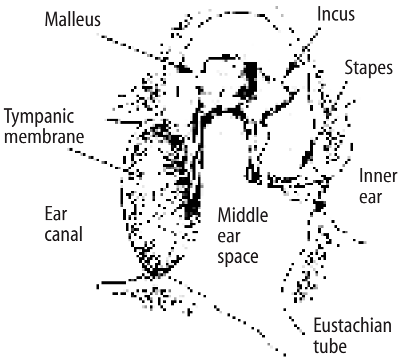


Figure 1.17 Tympanic membrane and the three ossicles (by kind courtesy of http://depts.washington.edu/otoweb/).

attachment allows free motion of the malleus and incus. The movements of the incus are in opposition to those of the malleus, *i.e.* as the malleus moves medially the incus moves laterally. This causes a lever-type action between these two ossicles. This lever is one of the important mechanical devices involved in the functioning of the middle ear.

The head of the incus leads to the body and the *long process* of the incus (see Figure 1.16). The next ossicle, called the stapes or stirrup, is attached to the end of this process. The attachment between the incus and the stapes is such that any movement of the incus leads to movement of the stapes in the same direction. Therefore, as the incus moves in, the stapes moves in as well. The stapes is the third and last ossicle, making up what is called the *ossicular chain*.

The stapes bone has four main parts: the head, neck, arms or *crura*, and the *footplate*. The footplate is the end part of the stapes and resembles the part of a stirrup into which the foot is put when mounting a horse. This footplate is oval in shape and fits in an oval-shaped opening in the medial bony wall, separating the middle ear from the inner ear, called the *oval window*. In anatomical terminology, a window is an open space in a bony wall. The ligaments that hold the footplate in the oval window allow this part of the stapes to rock in and out of the inner ear. This rocking motion sets up waves in the fluid of the inner ear.

Figure 1.17 shows how the middle-ear structures fit together. It also shows that the tympanic membrane is significantly larger in area than the footplate. This area difference is important and is discussed below in the section on middle-ear functioning.

1.5.3 The Middle-ear Cavity

The structures of the middle ear are situated in a part of the *temporal bone* of the skull known as the *mastoid process*. The tympanic membrane is attached to an opening in the bony walls making up the outer-ear canal leading to the middle ear. The bony middle-ear walls form a cavity known as the *middle ear* or *tympanic cavity*. In contrast to the bony ear canal, which is covered by skin, the walls of the middle-ear cavity are covered with *mucous membrane* (Figure 1.18).

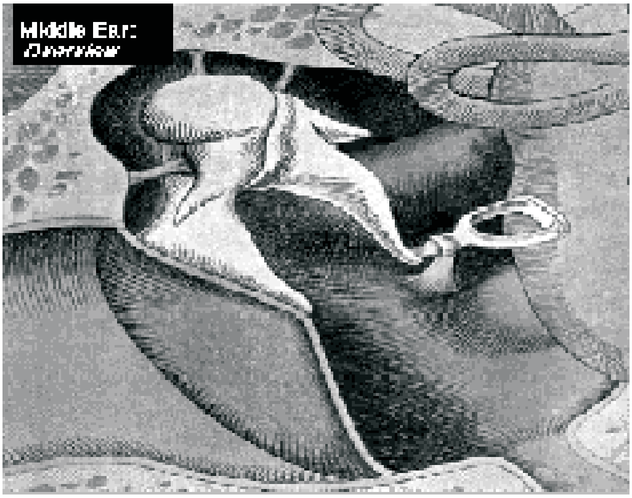


Figure 1.18 The middle-ear cavity (by kind courtesy of http://www.neurophys.wisc.edu/~ychen/auditory/anatomy/).

Attached to the walls of the middle ear are ligaments and other attachments that hold the ossicles in place. The *tympanic ring* is a cartilaginous ring in the most lateral part of the middle ear that holds the tympanic membrane in place. The superior portion of the middle-ear cavity is called the *attic*. The attic is a bony shelf, above which is the brain. Therefore, the middle ear is separated from the brain only by this bone. The bony walls of the attic are filled with holes or cells, known as the *mastoid cells*.

The medial wall of the middle-ear cavity contains the oval window, as described above, and has two other prominent features. The first is another window or hole in the bony wall; this is round and is called the *round window*. This window is covered with a membrane called the *round window membrane* and it functions to relieve pressure from the fluid of the inner ear when the footplate of the stapes sets up waves in this fluid. This will be discussed further below in the section on inner-ear functioning. The other prominent structure is called the *promontory*, a part of the medial bony wall that sticks into the middle ear. The promontory is a portion of one of the channels of the inner ear called the *scala media*, which is discussed further below in the section on inner-ear structures.

The most prominent feature of the floor of the middle-ear cavity is an opening that leads to a long tube connecting the middle ear with the back of the throat near the adenoids. This tube is called the *auditory* or *Eustachian tube* and is a critical part of the middle-ear cavity.

As a cavity, there is no normal opening between the middle ear and the outer world. However the middle-ear cavity is full of air and the mucous membrane cellular structures lining the middle ear require oxygen. Thus, the cells of this mucous membrane use up air in the middle-ear space and this would eventually cause a vacuum if the air were not replaced. The Eustachian tube is the structure that allows replacement of the air that has been exhausted. It is normally closed in children, from toddler age to adult. Movement of the muscles attached to the lateral part of the Eustachian tube in the area of the throat makes the tube open and allows air to rush into the middle-ear cavity. This effect is often noticed when there is a change in air pressure such as when going up high into the mountains or flying in an aeroplane. Passengers in cars and planes usually swallow, yawn or do something else to cause the muscles to open their Eustachian tubes allowing an equalisation of pressure between the middle ear and the outer world.

1.5.4 The Functions of the Middle-ear Structures

The middle ear converts the acoustic energy of the sound received by the pinna and funnelled down to the eardrum into mechanical energy by the motions of the eardrum and the bones in the middle ear. In order to facilitate understanding of the reasons for this conversion of acoustic to mechanical energy and the purposes of the middle ear, the anatomy of the inner ear will be discussed briefly.

The inner ear is the portion of the ear beyond the medial bony wall of the middle ear. Its structures are housed completely in fluids. Thus, energy travelling through the inner ear is in the form of hydraulic energy. Since the inner ear is fluid filled, sound received by the outer ear must be transmitted to this fluid. Sound waves will lose energy in going from air to fluid, as there is an impedance differential between the thinner medium of air and that of the fluid. In essence, the fluids of the inner ear have the basic characteristics of seawater contained in a closed tube. The change from acoustic energy travelling in air to acoustic energy travelling in seawater would lead to a loss of about 99% of the transmitted sound. Thus, to make up for this energy loss, the middle ear acts as an impedance-matching device by allowing the signal at the end of the middle ear (the footplate of the stapes) to have a greater energy than the acoustic energy striking the tympanic membrane at the start of the middle ear.

The impedance matching function of the middle ear has two components: the size differential of the tympanic membrane and stapes and the length differential between the manubrium of the malleus and the long process of the incus. Since pressure is force per unit area, the reduced area of the stapes compared with the tympanic membrane means that the same force striking it will give increased pressure. Sound pressure striking the tympanic membrane makes only 70% of the membrane oscillate, *i.e.* an area of about 0.594 cm^2. As the footplate of the stapes is rigid, this oscillation causes all of it to oscillate, *i.e.* an area of 0.032 cm^2.

Thus, the ratio of the tympanic membrane to the stapes footplate is 0.594/0.032 = 18.6. Therefore, the area reduction from the tympanic membrane to the footplate is a factor of 18.6. This leads to an *area size ratio increase* in pressure between the tympanic membrane and footplate of 18.6, therefore, providing an increase is energy between the sound striking the tympanic membrane and the energy transmitted to the footplate.

However, this is not the only change that occurs. Between the tympanic membrane and stapes are two other middle-ear ossicles, the malleus and incus. These ossicles function as a lever that further increases the energy transmitted along their path. The energy increase due to the lever action is related to the difference in the length of the handle or manubrium of the malleus and the long process of the incus. The difference is a factor of 1.3 in humans. Thus, energy is increased by a factor of 1.3 due to this lever action.

Combining the energy increase due to the area size ratio with that due to lever action gives a total energy increase of $18.6 \times 1.3 = 24.2$.

Therefore, the middle-ear mechanical transformation of sound energy leads to an increase of about 24 times. This can be converted into SPL in dB to give $20 \log_{10} 24.2 \approx 28$ dB. Therefore, middle-ear impedance matching adds 28 dB to the sound pressure of the acoustic energy striking the tympanic membrane. The energy loss when going from air to fluid is about 30 dB. Therefore, the middle-ear impedance matching approximately cancels out this energy loss, so there is very little overall energy loss when sound enters the inner ear.

1.6 The Anatomy and Functions of the Inner-ear Structures

The entire inner ear is actually a hole in part of the skull known as the temporal bone. This hole contains a labyrinth of membranous structures that house the sensory cells of hearing and balance. Therefore, the inner ear has a *bony labyrinth* and a *membranous labyrinth* (Figure 1.19). The inner ear carries out two sensory functions, *viz.* hearing and balance, which are localised in the cochlea and the vestibular system respectively. The two sensory systems interconnect within both of these labyrinthine systems, but have unique sensory cells that react differently, to allow neural information about sound (hearing) and balance to be transmitted. The auditory part of the inner ear has two main components: the cochlea and the auditory nerve, *i.e.* the eighth cranial nerve, sometimes referred to as just the eighth nerve.

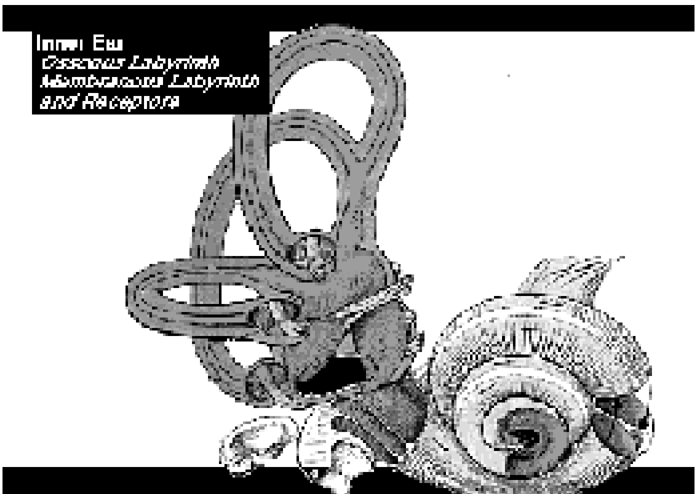


Figure 1.19 Inner-ear bony and membranous labyrinthine systems (by kind courtesy of http://www.neurophys.wisc.edu/~ychen/auditory/anatomy/).

The movements of the footplate of the stapes in the oval window set up waves in the fluids of the inner ear. It is at this point that the mechanical motions of the middle-ear structures are converted to hydraulic energy in the inner ear.

1.6.1 Vestibule

Beyond the footplate of the stapes is a fluid-filled area called the *vestibule*. Superior to the vestibule is a membranous structure consisting of two parts with three half-rings protruding from the superior part. The two parts are known as the *saccule* and *utricle*, and these are involved in providing information about body motion and movement in space. The three rings or canals protruding from the utricle are called the *semicircular canals*. Each of the three semicircular canals is oriented to one of the three dimensions of space: up-and-down, back-and-forth, and side-to-side (Figure 1.20). Thus, sensory information gathered from these canals provides information about our motion and movement in three-dimensional space.

Attached to one end of the utricle are a sac and duct known as the *endolymphatic sac* and *endolymphatic duct*. The sac produces endolymph, an inner-ear fluid that is found in the membranous parts of the inner ear. At the inferior end of the saccule there is a very narrow membranous duct that leads from the structures of the vestibular system to the membranous structures of the auditory system in the *cochlea*.

1.6.2 The Cochlea

The cochlear membrane differs from the vestibular membrane in many ways. One of the most important differences is that the membranous structures of

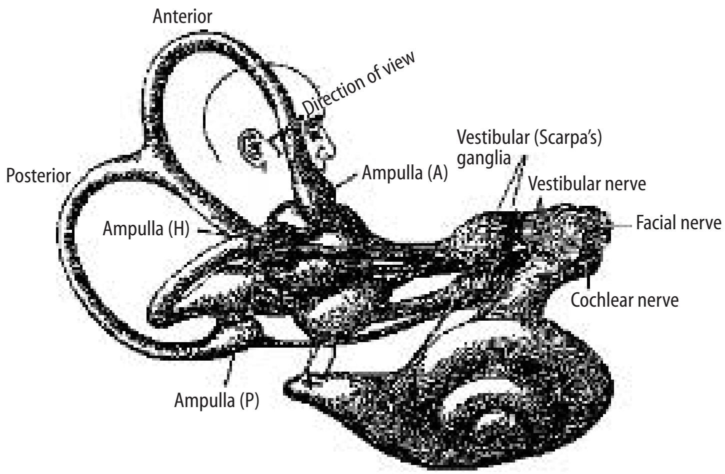


Figure 1.20 The balance system with the utricle, saccule and the three semicircular canals (by kind courtesy of http://www.anatomy.wisc.edu/Bs97/text/).

Figure 1.21 The cochlea (by kind courtesy of http://www.iurc.montp.inserm.fr/cric/audition/english/cochlea/).

the saccule, utricle and semicircular canals are floating in the fluids found in the bony labyrinth, whereas the cochlear membrane or *cochlear duct* is attached at the sides to the bony wall of the cochlea, and is only free to move on the top and bottom. This attachment leads to the formation of three chambers or canals called scalae (singular scala): one in the centre made of membranous walls, and the other two above and below this membranous cochlear duct.

The membranous duct is too long to fit into the small space of the bony cochlea section of the inner ear without folding and, therefore, curls like the shell of a snail. As shown in Figure 1.21, the cochlea has two and one-half turns.

The upper scala is mainly bone, with a membranous floor made from the superior membrane of the middle channel. It is called the *scala vestibuli*, since it comes from the vestibule. The bottom canal is also mainly bone, with a membranous ceiling from the inferior membrane or base of the cochlear duct. It is called the *scala tympani*, since it runs towards the middle ear or *tympanic cavity*. The middle cochlear duct is called the scala media and its floor and ceiling are entirely membranous (Figure 1.22).

The bony canals, scala vestibuli and scala tympani, are filled with perilymph, a fluid similar to cerebral spinal fluid and similar in viscosity to seawater. Perilymph flows throughout the bony labyrinth in both the cochlea and the vestibular system. The membranous canal or scala media, which is continuous from the duct connecting it to the saccule, is filled with endolymph.

The upper membrane of the scala media, called *Reisner's membrane*, is slanted. The floor or base of the scala media is made of the *basilar membrane*. It is on this membrane that the sensory cells of hearing are situated.

The sensory organ of hearing, known as the *organ of Corti*, is easy to see in Figure 1.23. It sits on the basilar membrane and consists of a series of cells, known as *supporting cells*, because they support the important sensory cells that transmit auditory stimulation to the central nervous system. The sensory cells are called *hair cells*, as they have *cilia* or hair-like structures protruding from them. It is damage, dysfunction, deterioration, or developmental problems with these hair cells that lead to the majority of permanent hearing loss often called *nerve deafness* or *sensorineural hearing loss*.

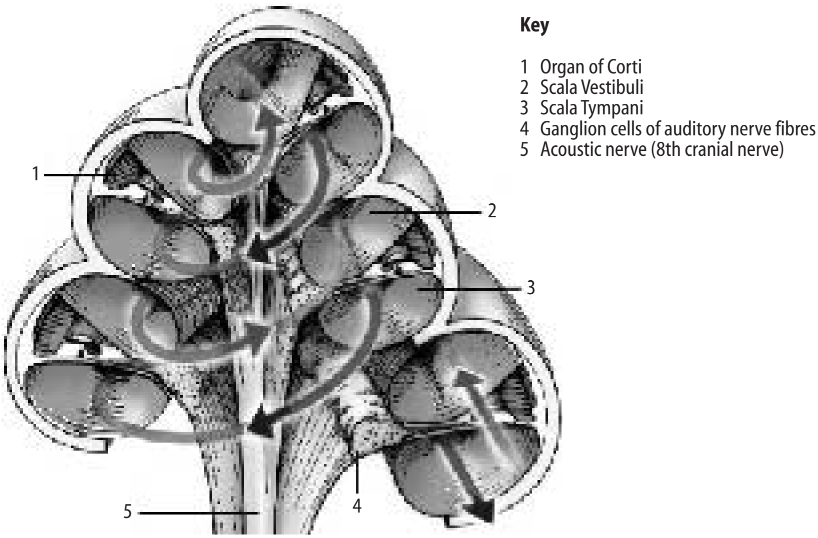


Figure 1.22 Cross-sectional view of the cochlea (by kind courtesy of http://www.iurc.montp.inserm.fr/cric/audition/english/cochlea/).

Figure 1.23 also shows that there are three hair cells followed by a structure looking like and inverted "V" followed by a fourth hair cell. The upside down structure is a supporting structure known as the *pillars of Corti*. The pillars of Corti support the *tectorial membrane* that sits on top of the hair cells. There are hair cells throughout the entire length of the scala media and they form rows of inner and outer hair cells. The *inner hair cells* are situated between the pillars of Corti and the innermost wall of the scala media. The remaining rows of hair cells are called *outer hair cells*.

At the base of each of the hair cells there is a small junction (space) in which are the neural endings of the *auditory nerve*. Stimulation of the cilia causes changes in these hair cells, leading to a release of neurochemicals into this junction called a *synapse*. The neurochemicals are picked up by the ends or *dendrites* of the auditory nerve and the neural transmission of sound sensation to the brain begins.

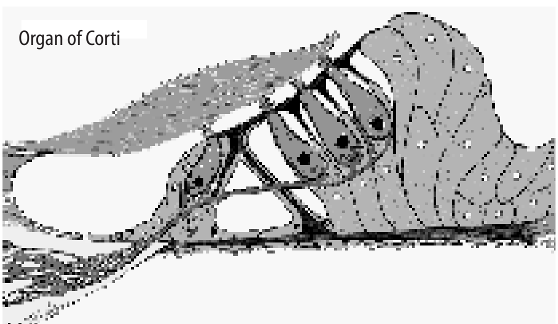


Figure 1.23 Organ of Corti (by kind courtesy of http://www9.biostr.washington.edu/cgi-bin/).

1.6.3 Sound Processing in the Cochlea

The movements of the footplate of the stapes are the final mechanical motion of the middle-ear structures. These movements cause waves in the perilymph fluid. The waves in the perilymph move from the oval window along the scala vestibuli to the helicotrema, which is the end where the scala vestibuli meets the scala tympani. The waves continue to flow along the scala tympani to the end of this canal. Since the perilymph is housed in a closed structure, the cochlea, there needs to be some release of the pressure that builds up as the footplate pushes into the fluid. This release is provided by the *membrane of the round window*, which covers a round opening in the bone at the lateral end of the scala tympani. Thus, as the footplate moves in, the round window membrane moves out, and *vice versa*.

As the wave moves along the scala vestibuli, its downward motion depresses Reisner's membrane, causing it to move down. Since the scala media is also enclosed and filled with endolymph fluid, the downward movement of Reisner's membrane compresses the endolymph, causing a downward displacement of the basilar member. Additionally, the tectorial membrane floating within the endolymph moves. While this is occurring, the basilar membrane is also moving down as the endolymph pushes the structures attached to this membrane. The motion of the tectorial and basilar membranes leads to a back-and-forth *shearing* action in the cilia attached to the hair cells. This shearing action leads to a change in the hair cells, thus causing the cell membrane at the base to allow neurochemicals to be released into the synaptic junction between the hair cells and the neurons of the auditory nerve (or eighth nerve) seated beneath.

The neural endings, or dendrites, pick up these neurochemicals and transmit them to the cell body, where they are stored until a sufficient quantity of neurochemicals has built up in the cell body, leading to a rapid and sudden discharge of the nerve cell called a *nerve impulse*. The nerve impulse flows down a long structure of the nerve called the *axon* and ends at the axon ending or foot. There, the permeability of the walls of the axon foot change. This allows a release of other neurochemicals into another synaptic junction, where awaiting dendrites from the next higher level neurons pick them up, move the neurochemicals to their respective cell bodies, leading to a neural discharge along their respective axons, releasing more neurochemicals into the synapses at their axonal endings. This neural transmission continues until the nerve impulses have brought the information to the brain for interpretation and comprehension of the message.

1.7 The Central Auditory Nervous System

As described above, the neurochemicals released by the hair cells are picked up by the neurons of the eighth or auditory nerve. The nerve impulses flow along the eighth nerve into the brainstem and eventually to the brain or *cortex*. The pathways from the eighth nerve to the brain are known as the *central auditory pathways* or the CANS. Transmission of information in the CANS is electrochemical, in the form of neurochemicals released into the synaptic junctions picked up by the next-level neurons causing a neural discharge.

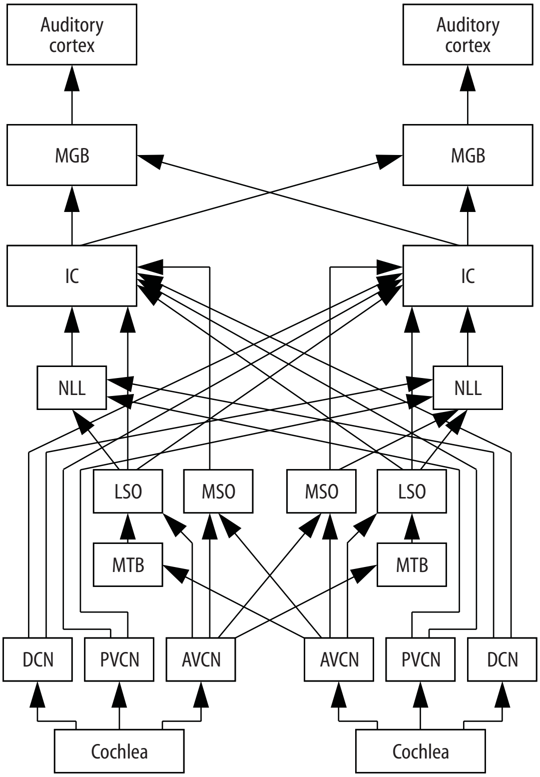


Figure 1.24 Block diagram of the pathways of the CANS (by kind courtesy of http://earlab.bu.edu/intro/).

The central auditory pathways are a complexity of neurons interconnected in intricate ways. Neurons function rather like capacitors, since they store neural energy until a level is reached at which they discharge totally, sending a DC voltage down the axon. Thus, neural activity is like direct current flow, in one direction, all-or-none, on-or-off.

The central auditory pathways, as with electric junction boxes, allow for multiple connections at each junction or synapse. That is, if one neuron leads to a synapse, there can be multiple neural connections at that junction. In this manner, neural information can flow to many different places from one source. Various junctions along the auditory pathways can be seen in Figure 1.24. The various blocks in the diagram have not been given in a key table since the figure is included only to provide an appreciation of the complexity of the pathways.

The first level in the system is at the eighth nerve, whose neurons begin at the base of the cochlear hair cells. The auditory nerve travels from the inner ear via a bony channel called the *internal auditory meatus* and enters the central nervous system below the brain or *cortex* at a level known as the *low brainstem*. Specifically, the auditory nerve projects to the *cerebellar–pontine angle* at the level of the *cerebellum* and *pons* within the upper end of the *medulla*. From there, these nerve endings meet with the next-level neurons at a region in the lower brainstem called the pons. This junction is known as the *cochlear neucleus*. Leaving the cochlear neucleus, fibres travel to either the next level in the system or bypass that level and jump to higher levels.

The next level above the cochlear neucleus is called the *superior olivary complex*. It is a complex of neural synaptic junctions. From the low brainstem, the pathway travels into the upper brainstem leaving the superior olivary complex, travelling along the *lateral lemniscus* to the *inferior colliculus* in the *mid-brain*. Here, the pathways project into a region of the brain called the *thalamus*. The auditory portion of the thalamus is called the *medial geniculate bodies*, since there are two: one on the right side and one on the left side. From here, neural fibres radiate out into the higher levels of the brain known as the *cortex*. Most nerve fibres project to the auditory receiving areas of the cortex known as *Heschl's gyrus*. From here, there are intricate connections to other parts of the cortex, between the right and left parts or *hemispheres* of the cortex, and, eventually, to areas of memory, visual regions, language regions, *etc*. Thus, the auditory pathways can be viewed as a complex system of "wires" with multiple connections and multiple routes through which neural discharges flow. This all-or-none discharging provides sufficient activity in the brain to make sense of sound, so long as all of the structures are functioning properly, coordinated in their functioning, and sound energy striking the tympanic membrane is transmitted to the inner ear and travels to the brain.

1.8 Classification of Hearing Loss

In order to determine whether there is a hearing loss, and, if so, the type and extent of hearing loss, hearing measurement is required. This will be discussed in more detail in Chapter 2. Measurement of hearing generally includes measurement of both air- and bone-conduction thresholds. The *hearing threshold* at a particular frequency is the minimum sound pressure given in dB HL required to perceive that frequency. *Air conduction* refers to sound travelling through air and then through the whole auditory system, whereas *bone conduction* refers to sound travelling through the bones of the skull, thereby avoiding the outer and middle ears (Figure 1.25). Hearing loss is generally indicated by raised thresholds. There is an *air–bone gap* when there is a difference between the air conduction and bone conduction thresholds.

The main types of hearing loss are categorised as:

- conductive
- sensorineural
- mixed
- central.

Conductive hearing loss results when there is a problem in the outer and/or middle ears. In this case, there will be an air–bone gap, as sound travelling through the bone conduction pathway would be heard better than sound travelling through the air conduction pathway that includes the outer and middle ear. Consequently, air conduction thresholds will be raised, but bone conduction thresholds will be "normal".

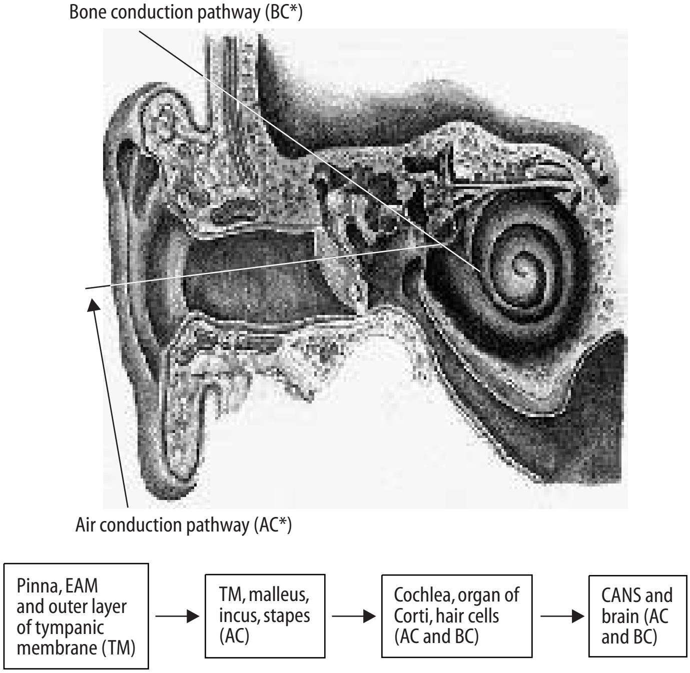


Figure 1.25 Air- and bone-conduction pathways (based on illustration courtesy of http://www.earaces.com/).

Sensorineural hearing loss results when there is a problem in the cochlea or inner ear. This can be further divided into *sensory hearing loss*, due to problems in the cochlea, and neural hearing loss, due to problems in the auditory nerve. Neural hearing loss is often referred to as *retrocochlear* hearing loss. In retrocochlear hearing loss, there is a lesion in the auditory nerve. It is relatively uncommon.

In the case of sensorineural hearing loss, both the air conduction and bone conduction thresholds are raised and there is no air–bone gap.

Mixed hearing loss occurs when there are problems in both the inner ear or auditory nerve and the middle or outer ears. This results in raised air- and bone-conduction thresholds, as well as an air–bone gap.

The last type of hearing loss is called a *central hearing loss*. Central losses are due to lesions, disorders, or dysfunctioning within the pathways of the CANS. In cases of pure central hearing loss, those without associated sensorineural loss, hearing thresholds are normal and there are no air–bone gaps. Central hearing losses lead to distortions in the processing of auditory messages rather than the loss of hearing sensitivity that is accompanied by the other three types of hearing loss.

This information is summarised in Table 1.1.

Measurement of the degree and type of hearing loss can be used to help diagnose problems in the auditory system. In most cases, it is the type of hearing loss that helps identify possible auditory disorders and ear "pathologies". The initial concern may be with the hearing loss, and there is a range of different

Table 1.1 Types of hearing loss and air- and bone-conduction thresholds.

Disorder of part of the ear	Air conduction threshold	Bone conduction threshold	Air–bone gap	Type of hearing loss
Outer ear	Raised	Normal	Yes	Conductive
Middle ear	Raised	Normal	Yes	Conductive
Outer + middle	Raised	Normal	Yes	Conductive
Cochlea	Raised	Raised	No	Sensorineural
Cochlea + outer	Raised	Raised	Yes	Mixed
Cochlea + middle	Raised	Raised	Yes	Mixed
Auditory nerve	Raised	Raised	No	Sensorineural
CANS	Normal	Normal	No	Central

causes. The majority of causes of hearing loss do not have any other consequences, but occasionally they are symptomatic of another problem, such as tumours.

1.8.1 Degrees of Hearing Loss

In addition to the type of hearing loss, the *degree of hearing* loss can also be categorised, using the hearing threshold. Slightly different categories are used in different countries. Table 1.2 presents the categories of degree of hearing loss defined by the American Speech–Language–Hearing Association (ASHA) and accepted in normal use by audiologists and hearing professionals in the USA.

Table 1.2 Degree of hearing loss.

Degree of hearing loss	Hearing loss range (dB HL)
Normal	−10 to 15
Slight	16 to 25
Mild	26 to 40
Moderate	41 to 55
Moderately severe	56 to 70
Severe	71 to 90
Profound	>90

1.8.2 Hearing Loss Due to Problems in the Outer Ear

Disorders of the outer ear generally cause conductive hearing loss, for instance due to blockage of the air conduction pathway. One common problem in the outer ear is the build up of cerumen (earwax), which can completely block the ear canal or EAM. In some cases, the build up of cerumen is so bad that the wax becomes impacted in the EAM and has to be syringed out by a nurse or doctor. Some of the other common outer-ear causes of hearing loss are outlined in Table 1.3. It should be noted that conductive hearing loss only results from problems of the outer ear if they result in total blockage of the air conduction

Table 1.3 Common problems of the outer ear that cause conductive hearing loss.

Problem	Structure involved	Causes and treatments
Cerumen	EAM	Cerumen softeners, ear washing (irrigation) or removal by doctor
Foreign objects in EAM	EAM	Irrigation or removal by doctor
Congenital atresia	EAM	Birth defect in which the ear canal does not form. Surgery is done for cosmetic purposes only
Otitis externa, outer ear infection (sometimes referred to as swimmer's ear)	EAM	Antibiotics and sometime anti-inflammatory medication to reduce swelling of EAM

pathway. For example, cerumen in the ear does not generally cause hearing difficulties until the wax totally blocks the EAM. This is also true of foreign objects and swelling of the ear canal. The conductive hearing loss lasts only as long as the outer ear is totally blocked and prevents sound reaching the tympanic membrane. Thus, most outer-ear problems cause temporary rather than permanent hearing loss.

1.8.3 Hearing Loss Due to Problems in Middle Ear

In contrast to the outer ear, there are a number of structures that can malfunction leading to problems with middle-ear transmission of sound to the inner ear. As with the outer ear, disorders of the middle ear lead to conductive hearing losses. The most common problems of the middle ear are infections and build up of fluid that may lead to infections, called *otitis media*. Otitis media can occur with effusion (fluid), with infection (acute), or as just a swelling of the middle ear with no fluid or infection present (just otitis media). In many cases, the middle-ear problems persist, leading to *chronic otitis media*. Otitis media with effusion is one of the most common causes of ear problems and temporary hearing loss in children. As with outer-ear disorders, many middle-ear problems are temporary and only cause hearing loss while they last. Table 1.4 presents some of the common middle ear problems identified by the structures involved.

1.8.4 Hearing Loss Due to Problems in the Cochlea

Unlike problems of the outer and middle ear, which lead to conductive hearing loss, problems involving cochlear structures cause sensorineural hearing loss. Disorders of the cochlea can involve problems with the sensory cells (*i.e.* hair cells and/or cilia), fluids of the inner ear, or problems with other structures.

The most common causes of sensorineural hearing loss are related to hair cell and cilia abnormalities. Such problems may be congenital in nature, due to abnormalities in the development of these sensory cells during the embryonic and foetal stages, or due to hereditary/genetic factors leading to abnormal development of these structures. Although less common, disorders may occur

Table 1.4 Problems of the middle ear that cause conductive hearing loss.

Problem	Structure involved	Causes and treatments
Perforated tympanic membrane (hole)	Tympanic membrane	Medicine to heal; time needed for hole to close; in some cases, surgery is required to close the hole
Infection/ inflammation of tympanic membrane	Tympanic membrane	Antibiotics and anti-inflammatory medicines to reduce swelling
Otitis media	Middle-ear cavity	Antibiotics if infection is present; decongestants; allergy medications if related to allergens; surgery to drain fluid
Otosclerosis	Stapes mostly footplate	Bony growth around oval window causes footplate to be immobilized; surgery to remove stapes and bony growth and replace with artificial device
Ossicular fixation	Any middle-ear ossicle	Two or more ossicles are fused or "stuck" together and cannot move; sometimes congenital; surgery to "unstick" the ossicles; sometimes surgery removes one ossicle and replaces it with artificial device
Ossicular discontinuity	Any middle-ear ossicle	Joints between ossicles break; can sometimes be congenital; surgery or device to connect ossicles

during the gestation period and lead to problems with the developing hair cells. For example, viruses that invade the mother, such as the rubella virus, can lead to hair cell abnormalities and dysfunction. Even rhesus blood incompatibility between the mother and developing foetus can cause destruction of hair cells in the newborn.

The most common causes of hair cell damage are noise and ageing. Exposure to loud sounds over long periods of time can lead to hair cell damage, especially involving destruction of cilia. This is often noted in people who work around loud noises and who do not use hearing protectors. The hearing loss associated with noise is known as *noise-induced hearing loss* (NIHL).

Presbycusis, due to the natural changes resulting from ageing, is one of the most common types of sensorineural hearing loss. It can involve a number of different structural changes in the cochlea, including hair cell deterioration, problems with blood supply leading to hair cell damage, and changes in other structures of the organ of Corti leading to transmission problems in the cochlea. Table 1.5 presents some of the most common causes of sensorineural hearing loss.

1.8.5 Problems in the Auditory (Eighth) Nerve and Central Auditory Pathways

Some problems affect only the auditory nerve, whereas others affect nerves within the central auditory pathways. In rare cases, both the auditory nerve and nerves within the central auditory system are involved. When a disorder affects the auditory nerve it is called a *retrocochlear disorder*. Such disorders

Table 1.5 Some of the most common pathologies causing sensorineural hearing loss.

Problem	Structure involved	Causes and treatments
Congenital	Hair cells, cilia, entire cochlea	Birth defects; problems picked up by the mother transmitted to the foetus; hereditary factors; rhesus factor; trauma
Neonatal	Hair cells; cilia	Infections picked up by the newborn; birth trauma
NIHL	Hair cells; cilia	Permanent hearing loss due to noise exposure
Temporary threshold shift	Hair cells; cilia	Temporary hearing loss due to noise exposure
Presbycusis	Hair cells; cilia; blood supply to cochlea	Normal changes in cochlea due to ageing
Ototoxicity	Hair cells; cilia; other cochlear structures	Drugs that are toxic to the cochlea, such as some mycin antibiotics and drugs used in cancer treatment, cause permanent hearing loss
Temporary ototoxicity	Hair cells; cilia	Drugs that are toxic to the cochlea only when high doses of the drug are in the person's system; most common is aspirin
Viruses and bacteria	Hair cells; cilia	Some viruses and bacteria can invade the cochlea and do permanent or temporary damage; one common bacterium is a form of streptococcus that leads to permanent hair cell damage and can also lead to encephalitis
Viruses and bacteria	Cochlear fluids	Some viruses and bacteria invade the intracochlear fluids, leading to dizziness and hearing loss, often temporary, only while disease is present in inner ear; sometimes referred to as labyrinthitis
Perilymphatic	Perilymph fluid	Hole (called a fistula) in the ligament holding footplate in the oval window or a hole in the membrane of the round window; loss of perilymph through the hole causes temporary hearing loss and dizziness; once hole is closed (spontaneous or by surgery), fluid returns to normal, as does balance and hearing
Ménière's syndrome or disease	Endolymph fluid	Improper absorption of endolymph leads to pressure build up in membranous channels of the inner ear, leading to dizziness and hearing loss that fluctuates with pressure changes
Advanced Ménière's	Perilymph and endolymph fluids, Reisner's membrane and hair cells	Advanced stages of Ménière's can lead to rupturing of Reisner's membrane, allowing perilymph and endolymph fluids to mix and cause ionic imbalance in cochlea that can cause permanent hair cell destruction
Cochlear otosclerosis	Perilymph, basilar membrane, hair cells	In some cases of otosclerosis the bony growth moves into the cochlea, invading the perilymph fluid and basilar membrane; can lead to damage to hair cells

cause sensorineural hearing loss (neural type). In contrast, problems in the auditory pathways of the CANS affect the ability to process and understand auditory information rather than hearing itself, *i.e.* the person can *hear* sounds but cannot *understand* them or interpret them as speech. If the problem is due to a lesion, such as a tumour pressing on one of the nerve pathways in the CANS, the disorder is called a central hearing loss. However, if the problem is merely related to interpreting auditory information in the absence of a lesion, the problem is called an *auditory processing disorder*.

The most common pathologies involving nerves relate to tumours or growths on, or that pinch, nerves, problems with blood flow to the nerves and other CANS structures, diseases (viruses or bacteria) that invade the nerves or CANS structures, or age-related degeneration of the nerve structures. These will all cause problems with the normal transmission of neurochemical substances or with nerve impulse transmission.

Trauma and accidents can lead to the destruction of nerves or CANS structures. Diseases that can cause deterioration of nerves are often referred to as *neurodegenerative diseases*. One of the most common of these neurodegenerative problems is referred to as *neural presbycusis* and is due to the natural changes and degeneration of the auditory nerves and CANS structures due to ageing.

One last site of neural problems involving central hearing loss is damage, disease, deterioration or related pathologies of the *auditory cortex* in the brain. This is the area of the brain (located above the ears) that is dedicated to the auditory sense. Hearing problems involving this area of the brain are often called *central deafness*. Table 1.6 presents some of the most common pathologies of the eighth nerve and CANS that include the brain.

Table 1.6 Pathologies of the auditory nerve and CANS pathways leading to hearing or auditory problems.

Pathology	Structure involved	Causes and treatments
Eighth nerve tumours	Auditory nerve	Abnormal cell growth of structures surrounding the auditory nerve; leads to sensorineural hearing loss; usual treatment is surgical removal, but radiation may be used to shrink them
Auditory neuropathy	Auditory nerve	Abnormal development or lack of development of the eighth nerve; wait to see if nerve pathway develops or permanent problems mostly with auditory processing
Congenital	Auditory nerve and CANS structures	Rare, but child could be born without an eighth nerve or other CANS structure including cortical; wait to see if nerve pathway develops or permanent problems, mostly with auditory processing; eighth nerve causes sensorineural hearing loss as well
Trauma/accidents	Auditory nerve, CANS structures, brain (auditory cortex)	Blows to the head; traumatic brain injury; depends on amount of injury, could be temporary, but is often permanent; auditory processing problems
Tumours of the CANS structures	Any structures in the CANS including the cortex, but excluding the auditory nerve itself	As with eighth nerve tumours, only these grow on the nerves of the CANS or in the brain (auditory cortex); surgical removal of tumour or growth; radiation or chemotherapy to shrink; leads to auditory processing problems
Cerebral vascular accidents (or stroke)	Burst blood vessel in CANS structural area or in brain (auditory cortex)	Leads to pressure in area, damage of cells in area; must wait to assess extent of damage; surgery may be tried to reduce swelling; leads to auditory processing problems

1.9 Medical and Non-medical Treatments

1.9.1 Medical and Surgical Treatment of Problems in the Auditory System

There are a number of different possible types of medical intervention. In many cases, as noted in the tables above, medical intervention involves prescribing medications and drugs to treat the diseases that affect the system. When medicines are prescribed, the hearing loss usually subsides as the symptoms are treated. In other cases, medication is unlikely to be successful because of the nature of the disorder (*e.g.* NIHL or trauma).

In addition to medicines, surgical interventions are prescribed in some cases, as noted in the tables. Usually, the surgery removes or corrects a problem, such as a tumour, but the hearing loss may still remain after the surgery. For example, if a tumour of the auditory nerve has led to a 60 dB hearing loss, removal of the tumour will leave the hearing loss at the same level. Additionally, surgery to treat or reduce serious, possibly life-threatening, problems, such as tumours, may, itself, cause greater hearing loss. For instance, removal of a tumour on the eighth nerve may require or result in partial removal or destruction of the nerve during surgery. This will have a serious effect on hearing.

When pathologies invade the nerves and CANS pathways, including the brain, radiation and chemotherapy may be tried. Again, the success of these interventions is the amount of reduction in swelling or growth, and, hopefully, total remission of the problem.

The professional who provides medical and surgical intervention is the ear, nose, and throat (ENT) physician, otologist, otolaryngologist, or otorhinolaryngologist. Some ENT physicians provide medical intervention only, but most of them can also perform surgery. Neurotologists (ear physicians specialising in disorders and surgeries of the auditory pathways) carry out surgical interventions involving the auditory nerve and CANS pathways.

1.9.2 Non-medical or Non-surgical Interventions

Audiologists are professionals who help to diagnose and provide non-medical/non-surgical treatment of disorders of the auditory system. The audiologist is trained to provide diagnostic, interpretive, and rehabilitative treatment using technological intervention, counselling, and what is called communication strategies, including the use of lip- and speech-reading.

Audiologists often evaluate, fit and even dispense or sell hearing aids. In some cases, people with hearing loss go to professionals who only fit and dispense or sell hearing aids but who are not trained in the diagnosis and rehabilitative treatment of hearing problems. These hearing health-care professionals may be called hearing-aid dispensers, dealers, fitters or audioprosthodotists. In many places, audiologists and hearing-aid dispensers are either certified or licensed (or both) to practise their professions, just as medical doctors are board certified and licensed. In some countries, individuals are able to obtain hearing aids as part of the state health system, whereas in others they have to purchase them privately or obtain them through medical insurance.

In many cases, medical or surgical treatments are not indicated or it is decided not to apply a medical or surgical treatment. For example, a person with otosclerosis for whom the surgery could be life threatening for a variety of reasons, or the degree of *otosclerotic growth* does not yet warrant surgery, could be fitted with a hearing aid. Assistive technology and various rehabilitative strategies could be used to improve communication and (auditory) access to sound.

For most people for whom medical or surgical treatment is not indicated, a hearing aid is the first step towards helping the person gain auditory access to sound. Although some people with hearing loss choose not to use hearing aids, these electroacoustic devices are still the most widely prescribe non-medical, non-surgical treatment for hearing loss.

When the hearing loss is too great to benefit from a hearing aid, but the person chooses to obtain auditory access to sound, a cochlear implant may be appropriate. These surgically implanted devices provide electrical rather than acoustic stimulation to the auditory nerve.

When a hearing aid or cochlear implant is not sufficient or for the deaf community (who prefer to remain deaf), assistive devices may be offered as well. The following chapters in this book provide a description of the devices available, including the technical principles on which they are based, and their application for persons who are deaf and hard-of-hearing.

1.10 Learning Highlights of the Chapter

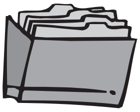
The chapter began with an overview of the facility of hearing. This was explored using two themes: one scientific, in which the acoustics of sound was investigated, and the other medical, in which the functioning of the auditory system was described. This second theme led, in turn, to medical conditions giving rise to hearing impairment and deafness.

Specific learning objectives were:

- gaining a basic understanding of the acoustics of sound, including how sound is propagated;
- understanding the anatomy of the auditory system, and learning how each part of the ear functions;
- understanding how hearing loss is measured and various degrees and types of hearing loss;
- learning about the main causes of the different types of hearing loss and the possible medical and non-medical treatments.

This chapter established a context for the measurement of hearing loss and provides the motivation to use technology assist those people who suffer a hearing loss or who are deaf. In the Chapter 2, the measurement of hearing and the science of audiology is studied. In Chapter 3, the engineering and scientific aspects of electronic hearing-aid prostheses are described.

Projects and Investigations



Understanding Amplitude, Frequency, and Phase (Sections 1.2.1, 1.2.2, and 1.2.3)

1. Draw two sine waves that differ in (a) amplitude and (b) frequency. Describe how the diagrams differ in amplitude and frequency, and what changes in sound and movement of the eardrum (tympanic membrane) and middle ear bones (ossicles) due to the changes in amplitude or frequency will occur.
2. Draw two sine waves of the same frequency and amplitude, one that begins at 0° phase and the other beginning at +90° phase. On adding these two sine waves together, what will be the resultant wave and amplitude?
3. Draw two sine waves of the same frequency and amplitude, one that begins at 0° phase and the other beginning at 180° phase. On adding these two sine waves together, what will be the resultant wave and amplitude?
4. What deductions can be made about adding sine waves of the same frequency and amplitude added together that start at different phases? How can shifting phase 180° and adding the two waves together be used in a sound system?

Understanding Sound Intensity and dB (Section 1.2.4)

5. Calculate the sound pressure for sounds having the following P_m values: (a) 40 μPa; (b) 200 μPa; (c) 200,000 μPa.

Understanding Line Spectrum and Wave Envelope (Section 1.2.6)

6. (a) Draw the line spectrum and wave envelope for the two sounds with the outputs at the given frequencies in the table below.

Sound 1		Sound 2	
100 Hz	10 dB	250 Hz	100 dB
200 Hz	20 dB	500 Hz	80 dB
300 Hz	30 dB	1000 Hz	60 dB
400 Hz	40 dB	2000 Hz	40 dB
500 Hz	50 dB	4000 Hz	20 dB
		8000 Hz	0 dB

(b) What type of complex sound is present in Sound 1 and in Sound 2?

Understanding Filtering (Section 1.2.7)

7. (a) In Question 6 above, one of the two curves represents filtering. Which curve represents filtering, and what is the amount of filtering expressed in dB per octave for that curve?

   (b) For the filter curve, does effective filtering occurs at: (i) 250 Hz, (ii) 500 Hz, (iii) a frequency between 250 and 500 Hz, (iv) 4000 Hz, (v) 8000 Hz, or (vi) a frequency between 4000 and 8000 Hz.

   (c) For the filter curve, what frequencies of sound will be heard after the filtering has occurred?

Understanding Anatomical Relationships (Section 1.3)

8. Look at the various diagrams in the anatomical sections of the chapter. Identify the components that are lateral, medial, anterior, posterior, superior, and inferior.

Understanding Physiology and Pathology Connections (Sections 1.8+)

9. In each of the physiological sections on the pathologies of the auditory system, mark the specific part or parts of the ear that are affected by each pathology. Identify the parts of the ear that are affected or "go wrong" when each pathology occurs.

References and Further Reading

Further Reading

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http://www.springer.com/978-1-85233-382-9

Assistive Technology for the Hearing-impaired, Deaf and Deafblind

Hersh, M.A.; Johnson, M.A. (Eds.)

2003, XIX, 319 p. 279 illus., Hardcover
ISBN: 978-1-85233-382-9