How do we hear?

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During the last decade there have been some tremendous advances in our understanding of how the ear works and how the auditory centres in the brain are connected together and process the information they receive form the ears. These advances in the understanding of normal auditory function also help to explain the causes of deafness and tinnitus. In many cases, this will lead to the development of better ways of treating and preventing hearing impairment.

The sounds which we hear, are due to the mechanical vibration of molecules in the air. Loudness and pitch of sounds are represented by the force and the frequency (number of vibrations each second) of the vibrations, respectively. Except for pure tones, which are seldom found in nature, the sounds we hear (for example speech) are made up of many different frequencies and intensities. The ear must detect these different characteristics and faithfully relay information on the sound to the brain where it is recognised in some meaningful way. The ear is thus a remarkable structure, which detects and "analyses" the minute patterns of vibration in the air which comprise the sounds we hear.

Sound causes the eardrum to vibrate and it is this movement, which is passed on to the inner part of the ear to excite the hearing nerve. The ear is extremely sensitive, being able to detect sounds, which are so soft that the movements they cause in the eardrum can only be measured by the most sophisticated electronic equipment. At the threshold of hearing, that is the softest sound, which an individual can hear, the eardrum only moves a billionth of a centimetre! Yet our ear is so sensitive that it can detect such minute movements and even distinguish a particular sound over the background noise. At the other end of the scale sounds may be so loud that the movement of the eardrum is excessive and causes pain. These extremes represent quite considerable differences in sound energy, yet whether the sound is the rustling of leaves in the forest or the roar of a jet engine; we are able to perceive them with almost equal clarity.

Compared with the ear of animals, the human ear detects sound over a fairly limited range of frequencies (or pitch). A young person with good hearing is able to hear sounds ranging from approximately 20 cycles each second (or Hertz (Hz) to 20,000 Hz. Compare this with bats, which can hear sounds up to 100,000, and pigeons, which are known to be able to detect sounds of less than 1 Hz. For a human, being able to detect sounds in the range 250 Hz to 4000 Hz is particularly important, as this is where most of the acoustic energy in speech sounds is concentrated.

Our hearing ability can be measured using various audiometric tests. The simplest is pure tone audiometry in which a pure tone is presented to the ear and the level is adjusted until it can no longer be heard. The hearing level, in decibels, at each of the test frequencies is displayed in an audiogram. Hearing levels are measured relative to the average hearing level of a population of normally hearing individuals.

A decibel (dB) is a measure of the intensity or level of the sound relative to a set intensity, in this case the intensity of the softest sound a normally hearing individual can hear. The ear can detect a very large range of sound energy. For example, a sound, which can cause pain, has approximately 1,000,000,000,000 times more energy than the softest sound we can hear. The decibel scale is a logarithmic scale, which compresses this large range of sound energy into a more manageable scale. Using the decibel scale, the above example would be represented by 0 dB (the softest sound) and 120 dB (the sound which causes pain). An increase of 10 dB represents a 10-fold increase in the energy.

To consider how the ear is able to perform all these remarkable feats, it is first necessary to look at its structure. However, it should be noted that the ear not only contains the organ of hearing but also that involved in balance. While the mechanisms of balance are not the subject of this article, it should always be remembered that the structures involved in the two functions of the ear are closely related and commonly affected by many different diseases.

The ear is "housed" in the temporal bone, one of the fused bones of the skull. The right and left temporal bones meet in the centre of the skull and form the floor of the brain cavity. Thus the innermost parts of the ear are quite deeply positioned in the head and are also close to the delicate tissues of the brain. This close proximity to the brain is the reason why some ear diseases can have a neurological complication and vice versa.

The ear is often considered to comprise three parts, these are the outer ear, the middle ear and the inner ear. The outer ear consists of the fleshy pinna and the skin-lined ear canal, which are the only visible parts of the ear. The pinna is very important for "tunneling" sound into the ear canal and plays a major role in the localisation of sound. Additionally the outer ear protects the delicate structures of the middle ear.

The skin lining the ear canal produces wax (cerumen), which has antibacterial properties and helps to keep the ear canal moist.

At the end of the ear canal, approximately 2.5cm from the entrance, lies the thin cone-shaped eardrum. This separates the outer and the middle ears.

The middle ear covers an area about the size of a fingernail and is only a few millimeters deep. It is filled with air and the pressure inside the middle ear is maintained at a pressure similar to the outside by a tube, the Eustachian tube, which opens into the back of the throat, near the tonsils.

This tube normally opens and closes during swallowing thus constantly maintaining the middle ear pressure similar to that of the outside air. If the pressure inside the middle ear is grossly different to the outside then the eardrum becomes stretched and does not vibrate correctly. This can often be experienced when flying as the pressure changes outside more quickly than in the middle ear as the plane ascends or descends.

Inside the middle ear are the three smallest bones in the body, called the malleus (hammer), incus (anvil) and stapes (stirrup). These tiny bones or ossicles (the

smallest is about the size of the "T" in this text) are connected together at joints and the whole chain is suspended in the middle ear by thin ligaments.

The ossicles connect the eardrum to the inner ear, the critical portion of the ear where the mechanical vibrations are finally converted into "messages" in the auditory nerve. The last of the bones in the chain, the stirrup bone, slots into one of the two small windows in the inner ear, called the oval window, which are covered by a thin membrane. The second window is known as the round window.

The inner ear consists of a coiled tube in the shape of a snail-shell, called the cochlea, and a number of other tubes, called the semicircular canals and vestibule, which contain the balance organs. The inner ear is about the size of a large marble.

The inner ear is filled with fluids, which are very similar in composition to seawater. There are actually two spaces inside the inner ear, which are separated by thin membranes and filled with fluids of slightly different composition. These two fluids are known as perilymph and endolymph. Lymph means "watery fluid that bathes tissues" and "peri" and "endo" refer to "around" and "within" respectively. Thus the tube containing endolymph is surrounded by that containing perilymph. It is very important to the function of the inner ear that these two fluids remain separated. Disturbances in the volume or composition of either of the fluids are known to be the cause of some types of hearing loss, such as Menieres disease.

Within the cochlea and spiraling around the snail-shell shape lies a thin strip of tissue called the organ of Corti (named after Alfonso Corti, who first described it in 1851) containing the minute hearing sensory cells. These cells, of which there are about 20,000 in a single ear, are known as hair cells because they have small hair-like structures projecting from their surface. In turn these cells are connected to a number of nerves which collectively make-up the auditory or "hearing" nerve. The hair cells are so small that approximately 100 cells placed side-by-side would fill the fullstop at the end of this sentence.

To complete the anatomy, the auditory nerve bundle (containing about 30,000 individual nerves) passes out of the cochlea and travels a few millimeters to the first auditory centre in the brain. From there the nerve branches and connects with many other nerves in the brain to send messages to the higher levels of the brain, the cortex.

In the process of sound detection a movement of the eardrum is transferred across the middle ear to the inner ear by the lever action of the ossicles. The movement of the stirrup bone in the oval window at the entrance to the cochlea of the inner ear sets up a small wave, which travels along the organ of Corti, causing the hairs on the hair cells to bend. When the hair cells are bent, chemicals from the surrounding fluid stream into the hair cell and result in the release of another chemical from the base of the cell. This latter chemical causes the nerve to discharge, sending a signal to the auditory centres of the brain.

Not all the cells of the cochlea are stimulated by each sound frequency or intensity. There are subtle differences in the structure of the cells and the organ of Corti along its length. For example the organ of Corti is very narrow and stiff at the base but becomes wider and "floppier" closer to the apex of the cochlea. These differences

cause any particular part of the organ of Corti to respond maximally to a particular frequency of sound. A high frequency sound tends to stimulate cells, and thus auditory nerves, at the basal part of the cochlea whereas lower frequencies stimulate progressively closer to the apex. In this way the cochlea "filters" the sound into its component frequencies. The brain recognises that signals coming from any particular location mean that a particular frequency was contained in the signal.

Some sound by-passes the middle ear and directly stimulates the inner ear by vibrating the bone of the skull. So why is there a middle ear? The middle ear bones are ingeniously designed to "amplify" the sound at the eardrum so that it can be efficiently transferred to the fluid-filled inner ear. When sound waves in air hit a water surface, as would be encountered if the oval window in the ear opened directly to the air, only a fraction of the sound energy passes into the water. (Next time you have a bath listen to how muffled sound, say from a radio, becomes when you put your head under water. In this case most of the sound from the source is being reflected at the surface of the water and only a little is reaching your ears.) The middle ear overcomes this by concentrating all of the sound at the large eardrum onto the substantially smaller oval window (the eardrum is about 18 times larger than the oval window), which has the effect of amplifying the sound by approximately 30 dB. Without a middle ear we would lose about 30-40 decibels of hearing.

Our traditional view of hearing has the sound stimulating the ear and establishing patterns of activity in the hearing nerve, which are relayed to higher auditory centres. We now realize that there are nerves, which transmit signals from the auditory centres in the brain to the ear. Some of these nerves innervate a small muscle attached to the stirrup bone in the middle ear. When stimulated by loud sounds the nerve causes the muscle to contract, which stiffens the ossicles and reduces transmission of potentially damaging sound to the inner ear.

Other nerves are now known to travel into the cochlea and are attached to one group sensory cells called the outer hair cells. The function of these nerves are not known but based on experimental studies it is clear that stimulation of the nerves can make the sensory cells less responsive to sound. Perhaps the auditory centres in the brain can regulate how the sensory cells function. This could be important to reduce the sensitivity of the ear to certain "unwanted" sounds (noise) so that a "wanted" sound can be heard. More research is clearly needed to determine the purpose of these nerve pathways.

Recently is has been shown that our ears actually emit very low-level sounds spontaneously or when stimulated by external sound. These sounds are called "otoacoustic emissions" and can only be measured in individuals with good hearing. It appears that when the ear is stimulated one group of sensory cells in the cochlea, the outer hair cells, rapidly oscillate or twitch, like minute muscles. This remarkably rapid movement is essential to the normal hearing process by making the ear more sensitive to very soft sounds. However, in the process some of the energy generated by the oscillation of these cells is transmitted back out of the ear and can be detected as sound by a very sensitive microphone in the ear canal. If these cells are damaged a hearing loss develops and the otoacoustic emissions diminish or disappear. Thus there is considerable interest in the mechanism and measurement of these emissions, including research being undertaken in the Department of Physiology at the

University of Auckland, as they could serve as a measure of inner ear function. Already there is evidence that otoacoustic emissions can be used to screen for deafness in babies.

This is a very brief discussion on some of the quite remarkable processes involved in hearing. The more one explores how the ear works the more one discovers how complex is this extraordinary organ and how magnificent is our sense of hearing.