Back

Sounds and Hearing, Pt. 2

We often take our hearing for granted. Find out how the ear works and what we can do to keep it functioning properly.

The idea of a mechanism that took hundreds of millions of years to develop is staggering. It was accomplished so slowly that you cannot observe any changes in your lifetime. In its present-day form, the ear, with its resulting construction, is so complex as to be overwhelming. To make matters more complicated, medical terminology can make a somewhat simple understanding even more intimidating.

THE EAR: A BIOLOGICAL TRANSDUCER

The hearing mechanism is very elaborate, and the brain's processing of information is more like a science-fiction story with an unfinished ending. Although volumes have been written about the hearing process, perhaps a few simpler explanations may help to understand some of the intricacies of the ear and how you hear.

The brain has a sound memory center that begins accumulating sounds almost at birth, perhaps even before. In normal adults, the brain has been able to establish a library of about 400,000 sound patterns to relate to the outside world. You can play tunes any time from your mental library, even complete symphonies with all the instruments playing together. In a similar way, nerve impulses from other sense organs, such as visual images or impulses from other parts of the body, can also be stored for comparison with new sensory input.

The ear is an incredibly sensitive device. The threshold of audibility corresponds to a pressure variation of less than one billionth of one atmosphere. This is commonly referenced as 0dB sound pressure level at 1000Hz, but varies with frequency.

At the other extreme, +130dB is considered the threshold of pain, corresponding to a voltage ratio of more than 3,000,000 to 1 (some sources quote +120dB as the pain threshold). Even a loud noise only causes microscopic movements of the eardrum. For a high-frequency sound, the motion may be only one-tenth of the diameter of a hydrogen molecule[8]. Hydrogen is in a diatomic form.

Although the ear magnifies a wide range of sound intensities, the transmitting equipment is too stiff to respond to the very weakest tones, and thus they are not heard. If the range were not limited, you would be assailed by such sounds as your own body's muscle contractions and bone movements.

A microphone can be called a transducer because it transforms energy from an acoustical system through a diaphragm to a mechanical system that is then converted to an electrical system. The ear functions as a biological transducer.

Figure 9 shows a cross-section of the ear[9]. There are three main sections: the outer, middle, and inner ear. The outer and middle ear function as an impedance transformer, converting energy from the low impedance of the air to the high impedance of the fluid in the cochlea.

Acoustic resonances in the auditory canal of the outer ear can double the sound vibration force. The mechani-

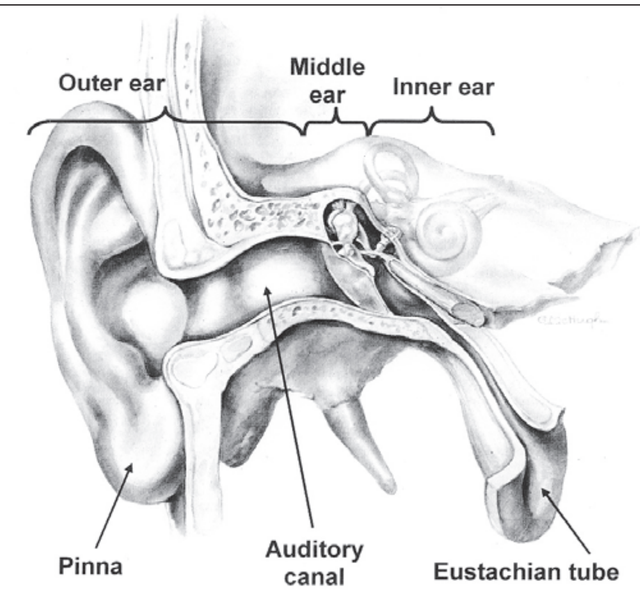

FIGURE 9: Cross-section of the ear.

cal advantage of the bone-lever system of the middle ear can triple it. Pressure then transmitted to the cochlea at the inner ear can increase it 30 times. The total result can be an amplification of up to 180 times before a sound wave sets the fluid of the inner ear in motion.

The principal parts of the ear can be seen in the three-dimensional model of **Photo 3**[10]. The sensitive parts of the inner ear are well protected inside the skull bone, shown as the porous structure. Sound travels from the auditory canal at the bottom left and ends at the eardrum near the bottom center. This converts the acoustic energy to mechanical energy that is transferred from the eardrum to the mechanical system of the middle ear consisting of three bones—the hammer, anvil, and stirrup (known collectively as the ossicles). These are shown just above the eardrum and are the smallest bones in the human body.

You can see the stirrup as a U-shaped bone at the center of the picture. The three loops at the top center of the picture are the semicircular canals that provide our sense of balance. They are part of the same bone structure as the cochlea, which resembles a snail shell and can be seen at the right side.

The stirrup transmits vibrations to the fluid-filled cochlea, which converts the energy into electrical pulses that are sent to the brain. The auditory nerves are shown just above the cochlea. The Eustachean tube is at the bottom right and is used to equalize air pressure on the eardrum. To put size in perspective, the cochlea is about the size of a pea.

The inside of the cochlea is hollow and is the most complex part of the hearing mechanism. A cross section is shown in **Fig. 10**. It is divided into three fluid-filled parts—the tympanic (lower) canal, the vestibular (upper) canal, and the cochlear duct (middle canal). They are separated by thin membranes. The upper and lower canals are filled with a fluid called perilymph, and the middle canal is filled with endolymph. These fluids have different chemical compositions and electrical charge.

The stirrup transmits vibrations to the oval window of the upper canal. Vibrations travel through this canal to the tip of the cochlea at its center, where the cross section is the smallest. The waves then enter the lower canal until they reach the membrane-covered round window at the large end of the lower canal. This window dampens the vibration.

The small rectangle enclosing the organ of Corti in **Fig. 10** is shown magnified in **Fig. 11**. The organ of Corti is a gelatinous mass located in the middle canal. It performs the most complex and interesting of the transformations and contains about 7,500 interrelated parts.

There are four longitudinal rows of auditory sensor hair cells. Three of the rows are outer hair cells and one row contains inner hair cells. They are embedded in supporting cells of the basilar membrane that forms the floor of the middle canal. Bundles of stiff stereocilia (much smaller hairs) project from the hair cells. Incidentally, stereocilia and stereo sound are not directly related.

The tectorial membrane shown in **Fig. 11** is suspended from the bone surrounding the cochlea and projects over the hair cells and stereocilia like a shelf.

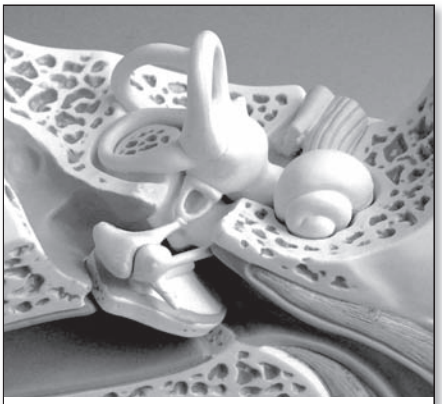

PHOTO 3: Inner ear model.

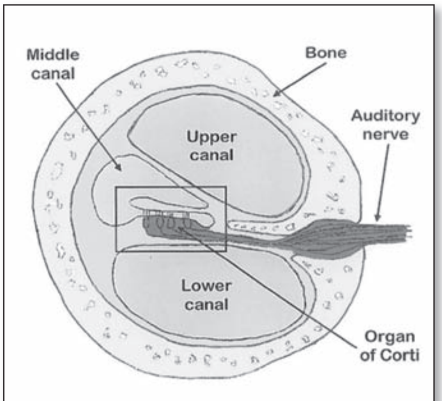

FIGURE 10: Cross-section of the cochlea.

It is coupled to the organ of Corti by the stereocilia bundles attached to the hair cells. There are over a million stereocilia in each ear. The fluid pressure waves produce motion of the basilar membrane that bends, twists, pulls, and pushes the hairs. This motion causes the stereocilia to move against the tectorial membrane.

The basilar membrane, also shown in **Fig. 11**, is light and taut near the wider stirrup end and thick and loose at the smaller end. Waves induce a ripple in the membrane. High tones produce their greatest crests where the membrane is tight; lower tones crest where the membrane is slack. The membrane can also pick up vibrations from the skull. When hearing is impaired, a bone conduction transmitter can sometimes be used to couple audio vibrations to the skull and restore partial hearing.

The chain of events for hearing then becomes even more involved with the conversion to electrical signals. The most intricate process occurs when motion of the stereocilia causes a chemical process to take place that alters the permeability of the membranes of the hair cells and allows positive ions to enter the corresponding cells. As a result, the respective cells develop a receptor potential and release more neurotransmitter molecules at its synapse with a sensory neuron. The resulting increase causes electrical discharges that are generated by the nerve cells. The cochlea-to-brain transmission system contains 30,000 nerve fibers issuing from the organ of Corti. The sound frequency interpretation depends on which fibers are activated.

Although there has been some correlation with nerve-firing rate and audio frequency, there is a recovery time for each nerve that limits the maximum firing rate to 1000 firings per second. This is a much lower rate than our upper limit of hearing at 20,000Hz. Nerves can take turns and increase the effective rate to 3000 firings per second, but information about most sound frequencies depends on which fibers are activated and not on the rate of firing.

Auditory nerve axons convey signals to the thalamus and cerebral cortex of the brain, where the auditory signals are interpreted as sound. Some signals are even fed back. The enormous amount of information transmitted to the brain can be selected and interpreted in an unbelievable number of ways. One that is commonly known is our ability to filter out a single conversation in a room full of people who are all talking.

SAFETY DEVICES OF THE EAR

The middle ear has inherent safety devices that help to protect the inner ear from loud noises and large changes in ear pressure. Loud noise in excess of 80 to 85dB triggers two sets of muscles. One tightens the eardrum and restricts its ability to vibrate, while the other pulls the stirrup away from its link to the inner ear. Sounds that are most damaging are those above 500Hz and protection mainly affects the range below 2kHz. Of course, there is a release time for the muscles as well. However, the protective system is relatively slow to act, being from 10 to 30ms for very loud sounds and up to 150ms for levels near the trigger threshold[11].

Typically, protection response is more effective for younger people. Nevertheless, hearing damage can still occur because there is a tendency to play music even louder, overriding the efforts of our ears to protect themselves. Hearing damage can occur at any age for very short duration high-level sounds such as a rifle shot or other acoustic spikes. The muscles do not respond fast enough.

You may have noticed that as you play music louder that the sound changes. Not only is there an apparent frequency shift, but the quality of the sound also seems to change. This is very apparent for some people, but others may not have noticed the effect at all. I attribute it to the action of the muscles of the inner ear and a listening level above 80 to 85dB.

The second safety device is the Eustachean tube, which connects the air-filled middle ear with the mouth cavity and serves as a pressure equalizer. This is why I was advised, when firing an anti-tank weapon, to open my mouth so that pressure would then be equalized at the eardrum and possible hearing damage could be avoided. This is similar to the operation of a noise-canceling microphone in which equal pressure at both sides of the diaphragm reduces diaphragm displacement. You may more commonly experience this when ascending or descending in an airplane.

HEARING DAMAGE

A normal hearing loss due to aging consists of a gradual decrease in high-frequency sensitivity over time. This means that for a man at age 35, hearing sensitivity could be reduced as much as 11dB at 8kHz. In comparison, for a woman at that age the reduction might be only as much as 5dB. This varies, of course, from person to person, but you can infer that sensitivity would be down even further at 20kHz[12].

On the other hand, hearing damage is an acquired symptom. Despite safety devices built into the human hearing mechanism, survival did not depend on tolerance to loud sounds. On the contrary, it depended on man's ability to hear and locate faint sounds. Humans are not equipped to tolerate exposure to so many loud sounds encountered in our present environment. Whether it is machinery, engines, or places of entertainment, the danger is there.

When it comes to car audio, home audio, and even headphones, you can be inadvertently attracted to the sensation of hearing and even feeling loud sounds and the sensation that the louder it is, the better. Unfortunately, prolonged exposure to excessively loud sounds or even short-term peaks can damage or destroy part or all of your delicate hair cells.

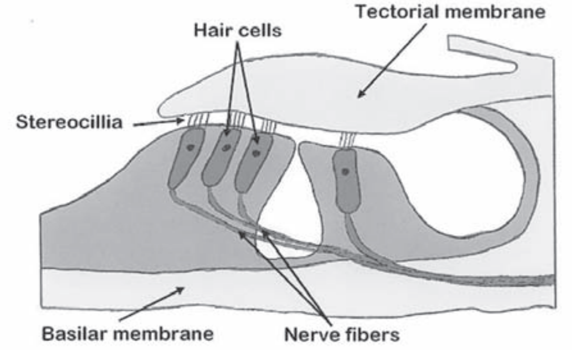

FIGURE 11: Cross-section of the organ of Corti.

They can become twisted, bent, and/or fused and are no longer able to respond properly to the incoming sonic vibrations. The ear's performance is degraded even when only a relatively small number of hair cells is damaged. The damage can be permanent in part or all of the frequency range for the rest of your life.

Hearing aids, which simply amplify frequency areas, might help to restore hearing to some degree depending on the severity of hearing loss. In cases of total hearing loss, cochlear implant surgery can be performed. Often, it is the stereocilia that are damaged and not the nerves. An implant can be effective in some cases and is becoming more common.

A typical operation involves inserting a tiny 22-channel electrode under the basilar membrane so that it curls around inside the cochlea. The electrodes stimulate the auditory nerves, bypassing the damaged hairs. An internal receiver is added near the cochlea with an antenna loop. An external microphone and amplifier are used outside the body.

The amplifier converts the audio signals to pulses, which are inductively coupled by placing the transmitting coil at the side of the head next to the receiver antenna implant. This operation can restore varying degrees of hearing, but not total hearing ability. Even if it restores only partial hearing, it is a tremendous help in reducing or lessening the feeling of isolation that total or near total deafness can cause.

A symptom of exposure to extra loud sound is ringing in the ears. This may go away after a period of rest, but repeated occurrences may someday cause permanent ringing.

For example, at one place of entertainment that used a loud public address system, I came prepared with a sound level meter and earplugs. It didn't take long for the sound to become very unpleasant, so I put my earplugs in and measured 85-90dB on the A scale and slow response. On the C scale with fast response, I measured 90-100dB. The PA system was used much of the time for about an hour.

I noticed later that one of the foam earplugs didn't fit tightly in my ear. Although I thought it cut down the intensity, when I removed both of them at the end of the performance, I could only hear well out of the ear with the completely sealed plug. Fortunately, this was only a temporary loss and my hearing recovered after 15 minutes or so. No warning was given to us that we would be exposed to uncomfortable or damaging sound levels. To quote from ASHA, "Sounds louder than 80 decibels are considered potentially dangerous. Both the amount of noise and the length of time of exposure determine the amount of damage."

Hearing damage is not just confined to adults. This can be even more prevalent with younger people, particularly those who use iPods with earbuds that are inserted directly into the ear canal. In a paper presented before the Audio Engineering Society[13], one researcher cited several audiological studies of students. In one case, it was found that 3.8% of the sixth graders failed a high-frequency hearing test, while 11% of 9th graders and 10.6% of high school seniors failed. A survey of incoming college freshmen yielded a 33% failure rate. The next year, 60.7% of the new incoming class failed. These figures clearly imply an accumulation of damage[14].

THE EMOTIONAL APPEAL OF LOUDER SOUND

Several difficult protective devices could be used but they can take away from the physical and emotional sensation of loud sound. To quote one disco enthusiasnt, "I like to feel the sound." The reasons people prefer louder sound have received little attention[15]. Loudness commands our attention. It's a survival trait. Louder sounds are usually associated with danger or excitement. They make the pulse go faster. They take your attention away from other lesser stimuli. In a sense, it is like a drug, providing an escape to a different space controlled by sound like the rhythm or the inventiveness of the music. The louder the sound, the more immersion there is in this other space. This immediate gratification would seem to be without penalty because the gradual increase in damage is not at first apparent. Warnings are then easy to ignore, and, like drugs, loud sound can even be habit forming.

CONCLUSION

In my opinion, sound in several dimensions has a long way to go to capture real acoustic events. However, so many improvements have been made in the last 50 years that music reproduction has become thoroughly enjoyable. For me, I only wish it had occurred at an earlier time.

There are two sides to pleasing sound. There is the re-production of reality and then there is the production of many alternate realities, all of which offer a different path to sonic ecstasies and all of which can provide many varied experiences. After all, the pleasure of music in various forms is what mankind has sought and expressed for many thousands of years. However, combined visual effects distract from a sonic experience and limit your imagination.

In addition, after this brief introduction to some of the delicate and very complicated functions of the ear, I hope that you will take care of your hearing and your children's hearing so that you may all continue to enjoy music and sound throughout your lifetimes. aX

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