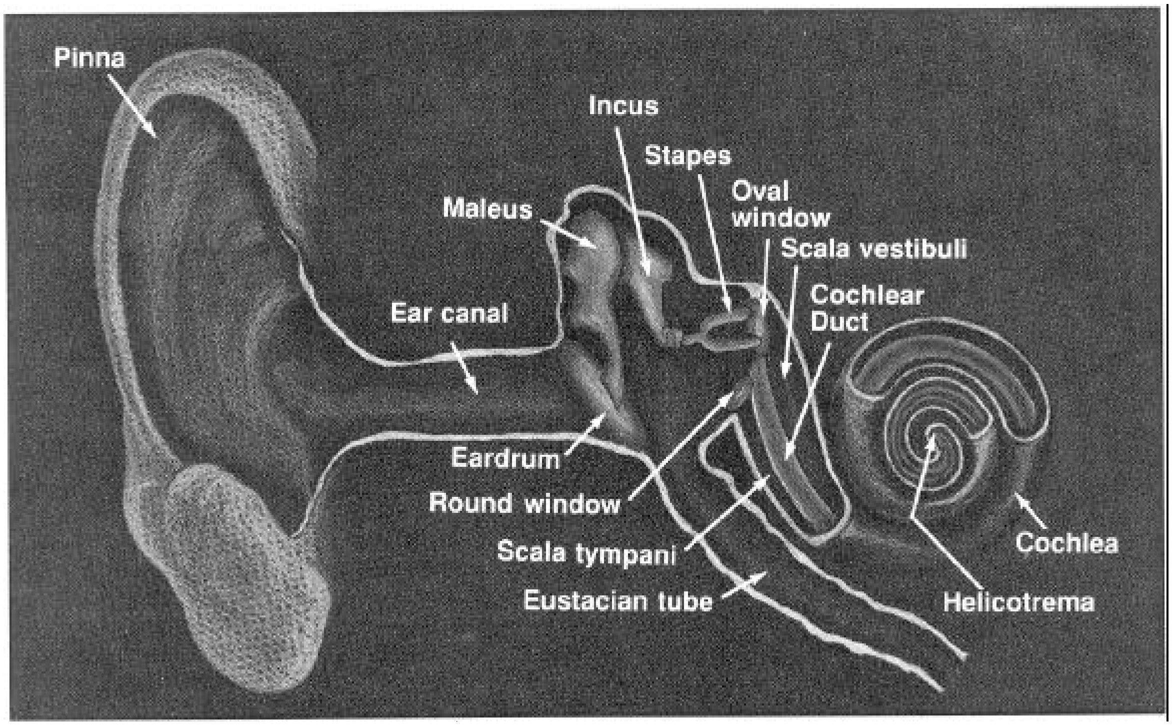
The physiology of the ear

By Ted Uzzle



Although the ear often receives less attention than the more sightly eyes, the ear is actually a more versatile organ with a greater dynamic range - 50dB greater, or 100,000 times the visual dynamic range.

Once you understand how intricate the auditory pathways are, you realize what a gift hearing is, and how important is the audio engineer's job of helping the hearing-impaired.

What is this strange and wonderful thing we call hearing? Consider the auditory sense in comparison to vision.

The threshold stimulus for vision is much less than for hearing. The dark-adapted eye needs only 0.5 attojoules (aJ) of energy falling on it to perceive light. The ear requires 100J of energy falling on the eardrum to perceive a sound.

In the comparative dynamic ranges of seeing and hearing, however, we find a dramatically greater versatility in the ear. The dynamic range of perception is the difference, in decibels, between the just-noticeable threshold and the level of stimulus that damages the sensory organ. The dynamic range of seeing is about 90dB — an extraordinary dynamic range by any standard. The dynamic range of hearing in a young person of moderate musical tastes is 140dB, 50dB more than for seeing; it is the visual dynamic range multiplied by 100,000.

The frequency response of perception is the range of frequencies over which the sensory organ operates, usually figured in octaves. The frequency range of visible light runs from the infrared to the ultraviolet, from 460 terahertz (THz) to 750THz, about 0.7 octaves. The frequency response of audible sounds, by contrast, runs from 20Hz to 20kHz, 10 octaves.

High-order brain processing is connected to the eyes and the ears, but I argue that more cerebral processing is employed for hearing than for sight. Consider, analogously, the simplicity of technical equipment required to analyze stereoscopic photographs and the sophisticated technical equipment needed to analyze sonar recordings. Consider that our ears are always active and that the sounds are always being evaluated, even while we sleep. When the baby cries or a burgler switches on the car engine, the sleeper awakens.

They are truly miracles, these things on the sides of our heads. Let's consider their anatomy and the way they work.

The outer ear

The part of the hearing mechanism presented to the outside world is a cartilaginous flap of skin called the pinna, or auricle. It has an asymmetrical shape useful in localizing the source of sound around the head. Though we are not accustomed to look at them closely, pinnas are just as individual as faces: No two are perfectly alike.

Running through the temporal bone of the skull is the ear canal, also called the auditory canal, the auditory meatus or, plainly enough, the earhole. Terminating the inside end of the ear canal is the eardrum or tympanum, also sometimes called the tympanic membrane. This is a circular plate of fibers, both radial and circumferential, attached to the ear canal all the way around its own circumference. It's quite easy to rupture the eardrum, and it usually heals quickly, but each rupture can stiffen the eardrum, and enough ruptures can affect the hearing.

The outer ear is inspected with an otoscope, an instrument with an internal light and a lens.

The middle ear

An open cavity within the temporal bone of the skull, between 1cm^3 and 2cm^3 in volume, contains the

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ossicles, which are three very small bones used to transmit the vibrations of the eardrum.

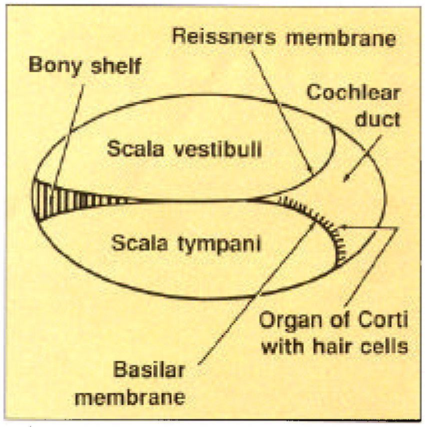
The outer bone is the malleus, or hammer. Its lower end is attached to the inside of the eardrum. Also connected to it is the tensor tympanum, a very small muscle that applies tension to the eardrum through the malleus. The upper end of the malleus is connected to the incus, or anvil, the second small bone of the middle ear.

The malleo-incudal joint is held together with semi-flexible tendons, and there is an unexpected phenomenon here. When the eardrum flexes inward, it pushes the malleus, which directly pushes the incus. When the eardrum flexes outward, however, it pulls the malleus with it, and the upper tip of the malleus actually separates from the end of the incus. The tendons at the joint stretch with each flexure. Therefore, from the middle ear on, the human hearing mechanism is asymmetrical. It responds instantly to compression waves pushing in the eardrum, but it responds with an elastic hysteresis to rarefaction waves that draw out the eardrum.

A lever motion of the malleus sets the incus into rocking motion. The inner end of the incus is attached to the stapes, or stirrup, the last of these tiny bones in the middle ear. The stapes moves linearly, driven at its smaller end by the rocking of the incus.

The larger end, the foot, of the stapes completely covers an opening to the innermost part of the ear. This opening is called the oval window. A muscle called the stapedius can pull down the tip of the stapes, away from contact with the incus. This action is called the acoustic reflex, and it is stimulated by over-excursion of the ossicles, usually the result of a very loud, impulsive sound. It provides about 20dB of vibration attenuation and requires about 175ms to take effect. The result is called a temporary loudness shift (TLS).

This hollow (but busy with activity) chamber, the middle ear, is connected to the rear of the throat by means of the Eustachian tube. This airway permits air pressures to be equalized between the two sides of the eardrum, but it can become clogged and provide a route of infection to the middle ear. The Eustachian tube is named after its discoverer, Bartolommeo Eustachio (1520-1574), an Italian physician and anatomist who worked in the days of the resurrection men, when human bodies could not legally be obtained for study.



The cochlea contains the scala vestibuli, the scala tympani and the cochlear duct, where vibration is converted into nerve impulse.

The inner ear

The foot of the stapes covers the oval window and moves back and forth with the vibrations of the incus (and, through the incus, with the vibrations of the malleus and, through the malleus, with the vibrations of the eardrum). The oval window is a flexible, membrane-covered interruption in a bony wall between the middle ear and the inner ear. All of the structures and organs of the inner ear are suspended within the membranous labyrinth. This is a series of communicating sacs and ducts, protected from the bony osseous labyrinth (the chambers within the temporal bone) by a form of spinal fluid called the perilymph.

The major organs of the inner ear are the cochlea and the semicircular canals. These are filled with a gelatinous, serous fluid, similar to the fluid inside cells, called endolymph. Once a vibration is transmitted by the stapes through the oval window into the inner ear, it becomes a fluid flow.

When the stapes compresses the fluid within the oval window, the fluid needs a pressure release. This is provided by the round window, or fenestra rotunda. The round window, like the oval window, is a membrane-covered opening in the wall between the middle and inner ear. When the stapes pushes the fluid in, the round window bulges back out into the middle ear.

Immediately within the inner ear is the vestibule, a chamber into which vibrations from the cochlea and the semicircular canals emerge. At the top of the vestibule, three curved tubes are arranged at right angles to each other so that each tube curves through one perpendicular plane of three-dimensional space. The upper tube is called the superior; it curves up. The rear tube is called the posterior; it curves horizontally. The tube at the side curves around the side and is called the lateral.

These three tubes, called the semicircular canals, are used to sense the orientation of the head. For this purpose, they are filled with otolith, or ear sand. This colorfully named stuff consists of crystals of calcium carbonate, which move across sensing hair cells in the semicircular canals. This works analogously to a carpenter's bubble level, except that, instead of a bubble finding the highest point of a curved tube, the ear sands drift around the lowest parts of curved tubes. They contribute to the sense of equilibrium and balance.

The cochlea

Now we come to the cochlea, the mystery at the center of human hearing. Its interior was first described in 1851 by Alfonso Corti (1822-1876). Great advances in the understanding of cochlear mechanics and electrophysiology were made throughout his life by Georg von Békésy (1899-1972), who started as an engineer with the Hungarian telephone company but found that his auditory researches gradually took over his career. In 1961, his research in ear anatomy won him the only Nobel prize ever given in any area of acoustics.

The cochlea is a helically coiled tube, which spirals about 2 times around a bony structure called the modiolus. It has three chambers running along its length. A very thin shelf of bone, called (appropriately) the bony shelf, or osseous spiral lamina, projects into the cochlea from the modiolus, dividing it almost in half along its length. At the tip of the bony shelf, two membranes spread apart, rather like the arms of the letter Y.

One of these is quite sturdy and is called the basilar membrane; the other is much thinner and more delicate and is called Reissner's membrane, after Ernst Reissner (1824-1873). Between these membranes runs the cochlear duct, or scala media. Within the cochlear duct are the structures that convert vibrations of the fluid to nerve impulses.

The channel running along the cochlea and Reissner's membrane, and connected to the oval window, is the scala vestibuli. The other major channel along the cochlea, the scala tympani, starts at the round window and runs along the basilar membrane.

These canals get smaller and smaller along the length of the cochlea, and at the apex are connected by a small opening in the basilar membrane called the helicotrema. The scala vestibuli and the scala tympani are filled with perilymph, which can flow through the helicotrema to equalize the static fluid pressures. When the stapes pushes on the oval window, fluid pressures are actually transmitted all the way up the scala vestibuli.

It is within the cochlear duct that the real action takes place. This canal is much smaller than the scala vestibuli or the scala tympani and is filled with endolymph, which is much thicker than perilymph. Running along the cochlear duct, and resting on the basilar membrane, is the organ of Corti. On one side, hair cells or cilia protrude into the cochlear duct; on the other side are the most peripheral nerve cells, called Corti's ganglion, of the auditory nerve (or eighth cranial nerve).

The hair cells in the organ of Corti actually terminate in a bundle of hairs, around 50 per cell. These are organized into a conical pattern, something like the stakes of a tepee. Electrically, the hair cells are capacitor plates. One end of the cell touches the perilymph on the other side of the basilar membrane; the other end, with the tips of hairs, floats in the endolymph.

Because the perilymph has a higher concentration of sodium ions and a lower concentration of potassium ions than does the endolymph (or, indeed, the interior of the hair cell), the resting hair cell has a potential of about −60mVdc. When the bundle of hairs is deformed in one direction by waves in the cochlear fluids, its potential is changed to about −40mVdc; when deformed an equivalent amount in the other direction, it is changed to about −65mVdc. This is yet another asymmetry in the auditory pathway.

These changes in the voltage of the hair cells affect the nerve cells immediately below. It is important, however, to remember that the nerve cell is not transmitting an analog current up to the brain. Nerve cells don't transmit continuously fluctuating signals. Rather, they electrochemically transmit impulses, or spikes; this is called nerve cell firing.

It is important to remember that the electrochemical behavior of the hair cells does not correspond precisely to the velocity or the displacement of the basilar membrane, which is why purely mechanical models of cochlear behavior yield so little useful information about hearing.

The auditory nerve brings impulses to the temporal lobes of the brain, that part of the brain immediately above the middle and inner ear.

You will sometimes find it said that a pure tone agitates only one very small area of the basilar membrane. This theory goes on to say that the way the brain knows what frequencies are being heard is by identifying which hair cells are in motion. That was actually believed by otophysiologists at one time, about a century ago.

It's true there are resonance behaviors within the cochlea, and the resonance antinodes occur at about 0.2 octaves per millimeter. Still, virtually every sound agitates virtually every hair cell in the cochlea. Frequency discrimination is a rather higher-order brain function than anything going on in the inner ear. There are good theories about how it works, but the theories rely on psychological testing as much as study of ear mechanics or electrochemistry.

The ear actually emits sound at frequencies the ear can hear properly. A damaged ear, with hair cell loss in the cochlea, will not emit sounds in the frequency ranges of hearing loss. This peculiar fact, disputed until recent years, suggests that active amplification, mechanical gain, occurs in the cochlea. The cochlear amplifier theory explains much about hearing that is otherwise inexplicable. There is no mechanism yet known by which the cochlea could amplify the vibrations transmitted to it.

A word about hearing damage

Helping the hearing-impaired is an important audio activity that has engaged the attention of the most inventive audio minds.

Johann Nepomuk Maelzel (1772-1838) is remembered best for his invention of the metronome, patented in 1815. The familiar wooden clicker with the upside-down pendulum is exactly as Maelzel built it 175 years ago. Maelzel also built an ear trumpet for Ludwig van Beethoven (1770-1827), which permitted the composer to hear his last sounds before complete deafness. The ear trumpet was a frightening affair, a giant tin horn blossoming from one side of the head, held in place by leather straps.

Thomas Edison (1847-1931) often wrote that his own partial deafness was the spur for his invention of the phonograph. At the end of his life an electronic hearing aid was built for him by Harvey Fletcher (1884-1981).

And, as we have seen, von Békésy, on whose work rests most of our understanding of the engineering aspects of the ear, was trained as a telephone engineer.

Every audio technician has a fundamental obligation to mitigate and ameliorate hearing damage, starting with his own ears. The audio engineer should be the first, not the last, to put his fingers in his ears when the sounds get too loud. The audio engineer should take the responsibility to see that sounds under his control don't get too loud for safety.

The ear is far more versatile than any other sensory organ. The auditory pathways are still poorly understood, but what is known of them makes the gift of hearing even fuller of wonder. **S&VC**

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