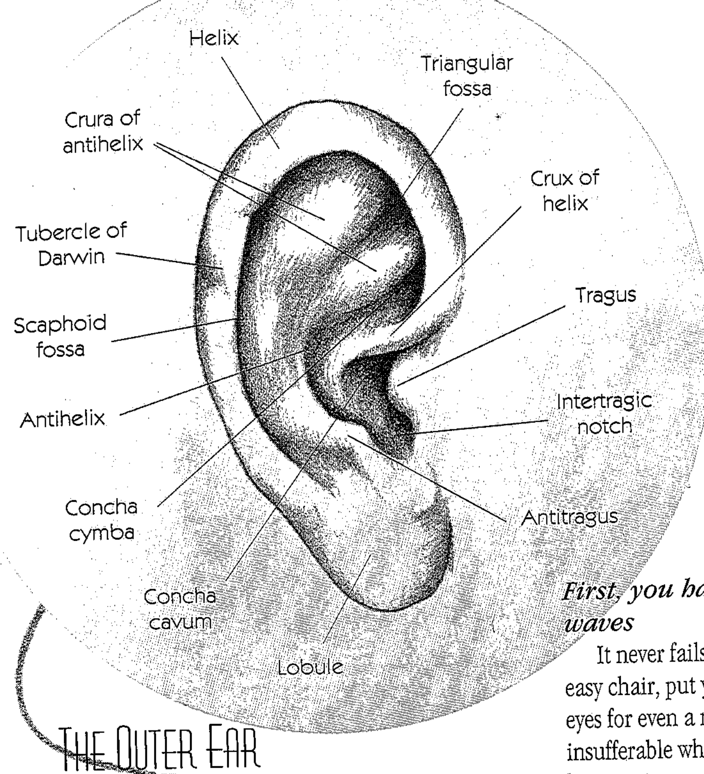
THE INSIDE STORY

by Ruth Brown



THE OUTER EAR

Your pinna—that fleshy flap on the side of your head—scoops up sounds and funnels them down into your ear.

> Like some crazy Rube
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> Goldberg device,
>
> your ear pushes on this,
>
> which rattles that,
>
> which pulls on this,
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> which pushes on that—
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> all to transform
>
> vibrations into the
>
> sounds you hear.

First, you have to believe in sound waves

It never fails. Snuggle down in your favorite easy chair, put your book in your lap, close your eyes for even a moment, and there it is: the insufferable whine of a hungry mosquito buzzing in your ear. How can such a little bug make such an annoying sound? It's those tiny little wings, vibrating hundreds of times each second, that makes the mosquito's buzzing sound. With each wingbeat, waves of disturbed air travel across the room and wash into your ear. The sound you hear is your brain's interpretation of these pulsating waves of moving air, which we call sound waves.

Once a sound wave gets inside your ear, its vibrations make their way through a gauntlet of internal gadgetry that might have been put together by a diabolical plumber: this bumps into that, which rattles this, which falls on that, which pulls on this, which pushes on that, which . . . well, you get the idea. Along the way, some vibrations die out—these are the sounds that you don't hear. Others are enhanced, smoothed out, and processed by your brain, so that you can hear the rumble of thunder or the shrill buzz of that hungry mosquito. Like some crazy Rube Goldberg device, your ear passes the vibrations of sound waves deeper and deeper into your head—first through air pressure in your outer ear, then mechanically in your middle ear, and finally hydraulically and electrically in your inner ear, where the signals are finally sent to the brain to be interpreted and perceived as sound.

The outer ear: more than just a place to hang your earrings

Way back in the sixth century B.C., the Greek mathematician Pythagoras figured out that sound was vibration. The classical anatomists knew that people heard sounds when these vibrations got into their ears. But although they did their best to puzzle out the mechanics of hearing, they were hampered by a philosophical squeamishness that kept them from actually looking inside the human ear. Instead, they studied what they could see—the outer ear. As a result, the pinna (that convoluted, fleshy flap on the side of your head) and the ear canal (the odd little tunnel that pokes in through the middle) are better defined, anatomically speaking, than you might imagine. In a fit of scientific exactitude, the first-century Roman anatomist Rufus of Ephesus gave every nook and cranny of the pinna its very own Latin name.

Although it may not be a thing of beauty, your outer ear is perfectly designed for what it does. Like the funnel it resembles, your pinna collects sound waves and directs them down to your middle ear. Every part of its unlikely shape helps support this process. Unlike dogs and horses and sheep and pigs—indeed, unlike most mammals—we can't move our ears. Though some people are better ear-wigglers than others, even those most adept at this dubious skill have to turn their head to follow a sound: we have to aim ourselves in the right direction.

This is where the bumps and whorls and ridges of your outer ear help out. They support the vibrations of sounds coming from some locations and suppress others. Your brain interprets this information to help you locate the source of a sound. (You can read more about how your ear locates sounds on page 16.) Without your pinna you can still hear, but you can't easily tell where a sound is coming from.

Once a sound wave makes its way through your pinna's fleshy maze, it gets shot pretty much straight into your ear canal, which extends from your outer ear down to your eardrum. Since your ear canal is essentially a tube that's open at one end and closed at the other, it manipulates sound waves in much the same way a pipe organ does. Like the sounds that swell in an organ sonata, sound waves that enter your ear are squeezed down and enhanced as they make their way to your eardrum. They bounce off the walls of your ear canal, reinforcing each other and setting up supporting reflections that magnify the pressure of the sound. By the time the sound of that buzzing mosquito gets to your eardrum, just an inch from where it entered your ear, it may already have doubled in pressure.

As the vibrations bouncing around in your ear canal reach the end of their journey, they smack into your eardrum, the tightly stretched membrane that separates your outer ear from your middle ear. Your eardrum responds to this barrage of pulsating pressure waves like the tightly stretched membrane of any drum would: it begins to wobble and bounce, vibrating along with the vibrations that hit it. At this point, the sound waves have done their job: they travel no farther than the eardrum. In the middle ear, mechanical movement keeps things going.

Tripping over the middle ear

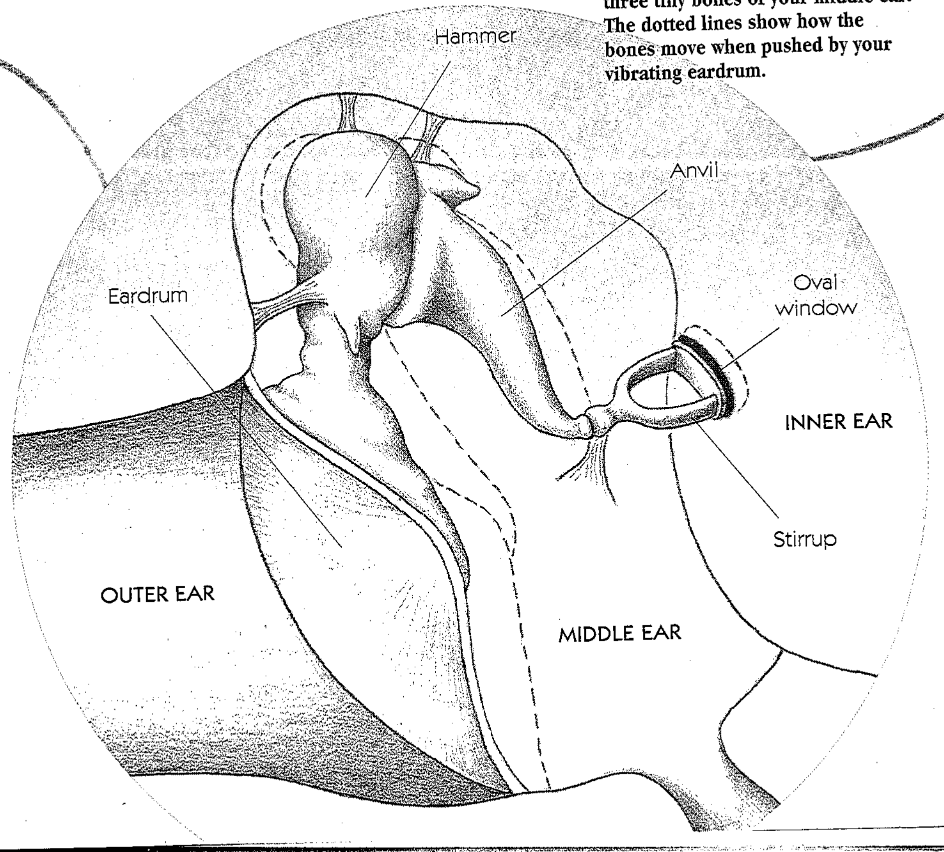
Your middle ear is essentially a bridge of three tiny bones, called ossicles, that transfer incoming vibrations from your outer ear to your inner ear. In 1514, when physicians were finally beginning to dissect the human body, Berengio da Carpi mentioned the existence of these bones, and his writings suggest that they had been discovered even earlier. But it wasn't until 1543 that Belgian anatomist Andreas Vesalius wrote what is considered the first accurate description of the ossicles and their function. And even then, he practically tripped over them. "When I was cleaning out a skull for preparation of a skeleton," he wrote, "an ossicle chanced to fall out of the ear. I opened the auditory organ in a fresh skull and with that ossicle I found a second."

Vesalius had found two of the three bones of the middle ear. He named them the *malleus* (hammer) and the *incus* (anvil) for their shapes and functions—the hammer, as it were, beating on the anvil. The third bone, no bigger than a grain of rice, was identified a few years later by Gian Filippo Ingrassia at the University of Naples. He called it the *stapes* (stirrup), because "it was the shape of the stirrup or footpiece of our ancestors."

These three little bones sit in a pocket of air about the size of an ordinary sugar cube. They're connected to each other like a set of tiny levers. Since the first bone (the hammer) sits right on top of the eardrum, it moves when your eardrum moves. The moving hammer pushes and pulls on the second bone (the anvil), and that activates the third bone (the stirrup) to press on the opening to the fluid-filled inner ear. Just as pushing down on one end of a seesaw can lift a heavy person on the other side, each movement of an ossicle amplifies the force of the movement before it. As a result, the slightest quiver of your

THE MIDDLE EAR

At the end of your ear canal, on the other side of your eardrum, are the three tiny bones of your middle ear. The dotted lines show how the bones move when pushed by your vibrating eardrum.



THE EAR

Outer Ear

1 You may not think of your outer ear, called the PINNA, as a thing of beauty, but if you gently follow the path of its whorls and ridges with your finger, you can get an idea of its function. Your pinna collects sound waves and funnels them into your ear canal. It also helps you locate the source of a sound. (You can find out more about sound localization on page 16.)

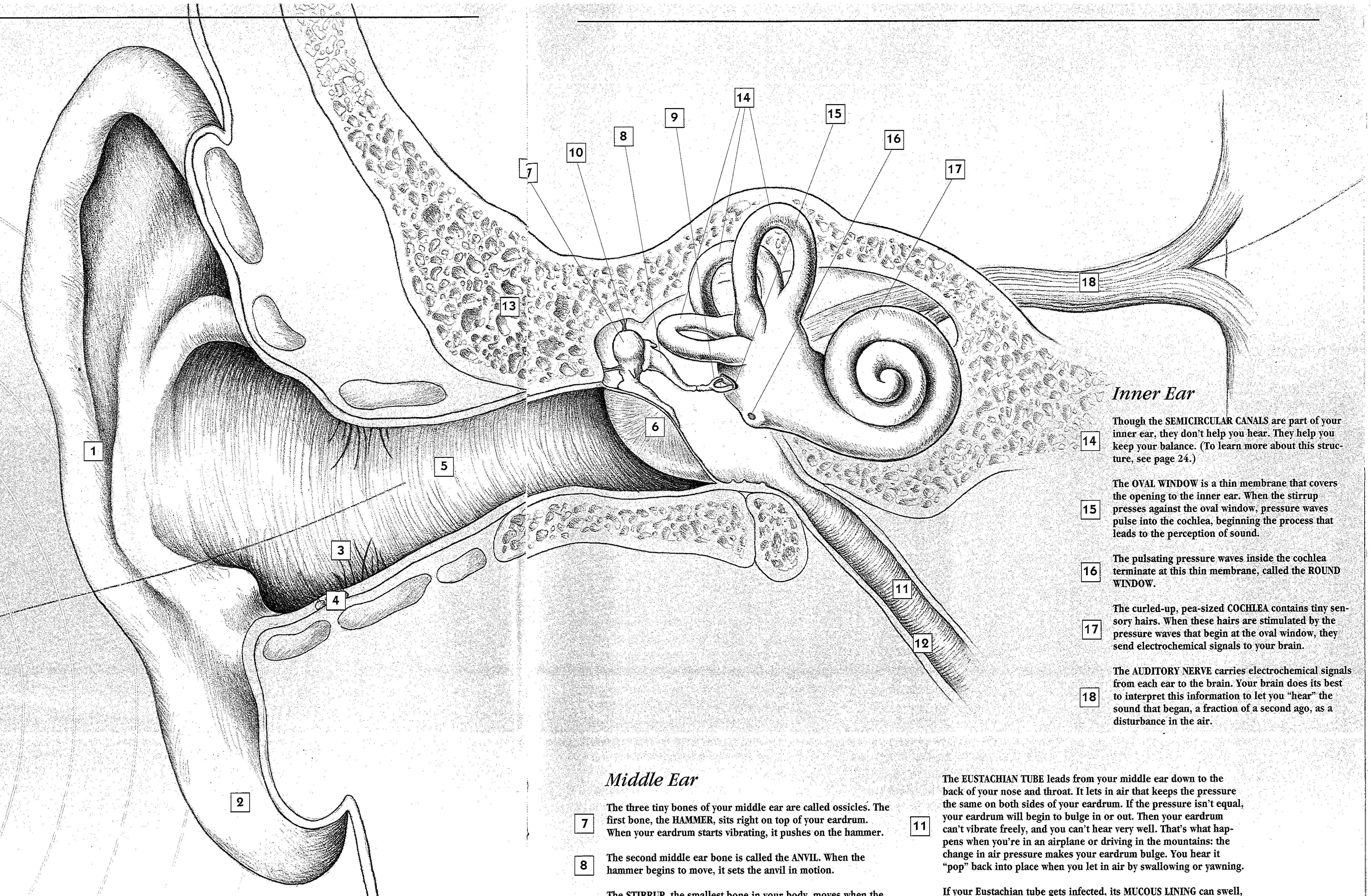
2 Unlike the rest of your pinna, which is made of cartilage covered with skin, your EAR LOBE is made of soft connective tissue. Use your hand to feel the difference.

3 HAIR FOLLICLES line your ear canal. If you have lots of bristly hair inside your ears, take comfort in knowing that your ear canal is well protected from dirt, dust, and foreign invaders.

4 Specialized SWEAT GLANDS make sticky yellow ear wax that lubricates your ear canal and traps any nasty stuff that makes it past the protective hairs. Once something is trapped in your ear wax, the wax loses its stickiness, balls up, and falls out naturally.

5 Your EAR CANAL—a tube about the size of a pen cap—channels sound waves down to your eardrum. The layer of skin that lines your ear canal gets thinner and more sensitive as it nears the eardrum.

6 Your EARDRUM is a cone-shaped membrane that stretches across the back of your ear canal. Your eardrum vibrates when it's hit by the sound waves that travel down your ear canal.



Inner Ear

14 Though the SEMICIRCULAR CANALS are part of your inner ear, they don't help you hear. They help you keep your balance. (To learn more about this structure, see page 24.)

15 The OVAL WINDOW is a thin membrane that covers the opening to the inner ear. When the stirrup presses against the oval window, pressure waves pulse into the cochlea, beginning the process that leads to the perception of sound.

16 The pulsating pressure waves inside the cochlea terminate at this thin membrane, called the ROUND WINDOW.

17 The curled-up, pea-sized COCHLEA contains tiny sensory hairs. When these hairs are stimulated by the pressure waves that begin at the oval window, they send electrochemical signals to your brain.

18 The AUDITORY NERVE carries electrochemical signals from each ear to the brain. Your brain does its best to interpret this information to let you "hear" the sound that began, a fraction of a second ago, as a disturbance in the air.

Middle Ear

7 The three tiny bones of your middle ear are called ossicles. The first bone, the HAMMER, sits right on top of your eardrum. When your eardrum starts vibrating, it pushes on the hammer.

8 The second middle ear bone is called the ANVIL. When the hammer begins to move, it sets the anvil in motion.

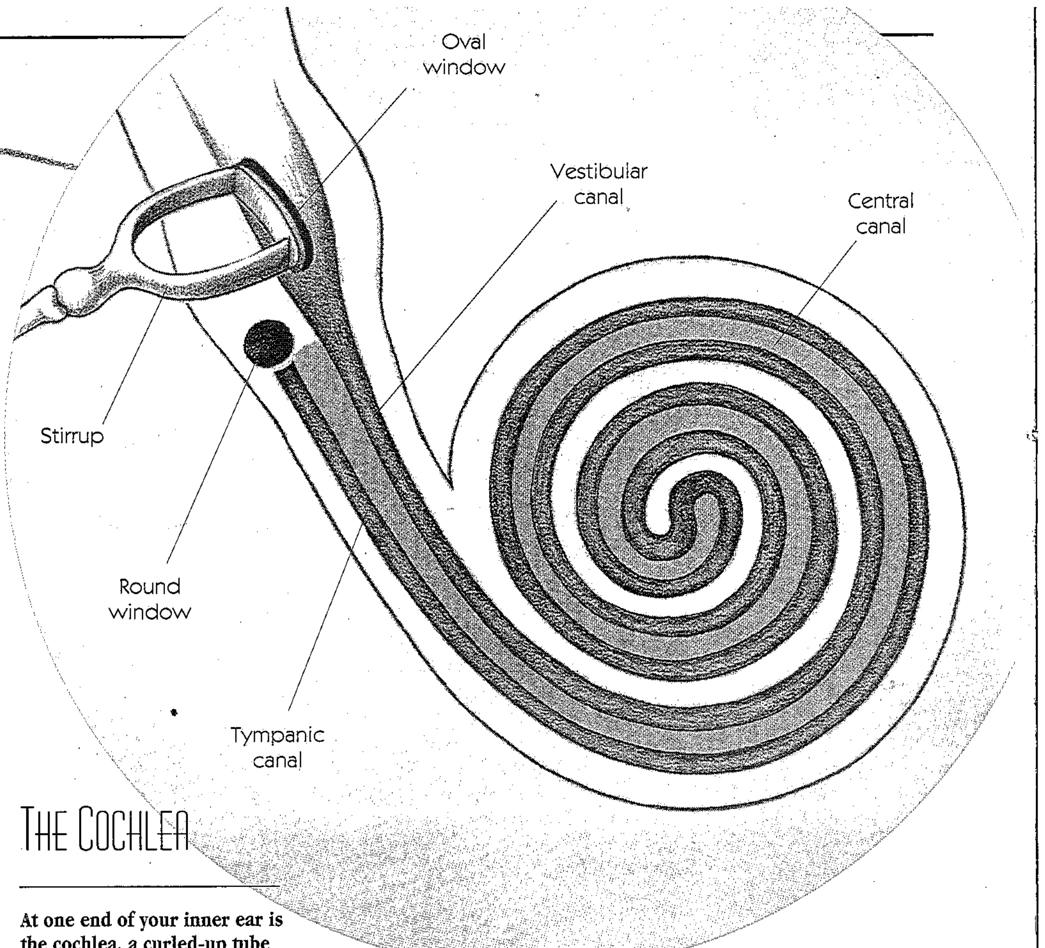
9 The STIRRUP, the smallest bone in your body, moves when the anvil pushes on it, pulsing rhythmically against the opening to your inner ear.

10 Besides anchoring the ossicles, tiny MUSCLES OF THE MIDDLE EAR serve as built-in safety devices. If a sound begins to get too loud, one muscle pulls the eardrum tight so that it can't be damaged by vibrating too wildly. Another muscle twists to the side so the stirrup can't press too hard on the inner ear. If a sound happens too suddenly for these muscles to work, the result can be serious ear injury.

11 The EUSTACHIAN TUBE leads from your middle ear down to the back of your nose and throat. It lets in air that keeps the pressure the same on both sides of your eardrum. If the pressure isn't equal, your eardrum will begin to bulge in or out. Then your eardrum can't vibrate freely, and you can't hear very well. That's what happens when you're in an airplane or driving in the mountains: the change in air pressure makes your eardrum bulge. You hear it "pop" back into place when you let in air by swallowing or yawning.

12 If your Eustachian tube gets infected, its MUCOUS LINING can swell, making it almost impossible to let in enough air to equalize pressure on your eardrum. That's why your ears get stuffed up when you have a cold or the flu. In small children, the space between the Eustachian tube and the ear is so short that infection can easily move into the middle ear.

13 When you speak, vibrations from your voice reverberate through the BONES OF YOUR SKULL and move directly to your inner ear. That's why you sound so different on a tape recording: you hear only the airborne sounds you make, not the more complex sounds that bounce around inside your body.



THE COCHLEA

At one end of your inner ear is the cochlea, a curled-up tube lined with sensory hairs, where the processes of real "hearing" take place.

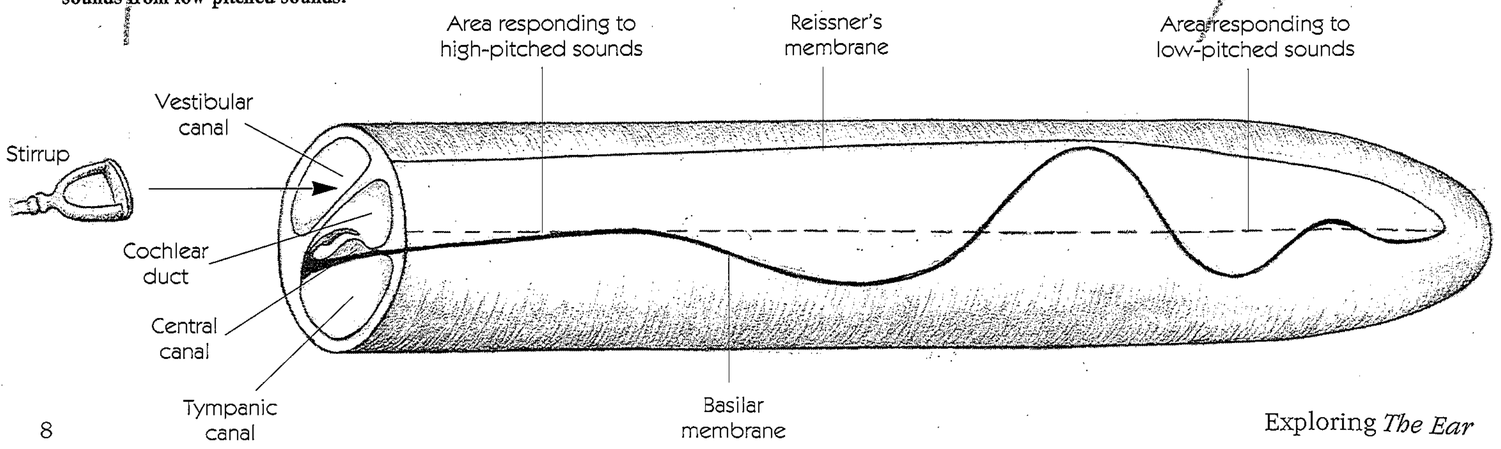
eardrum may be tripled in force as it moves from the hammer to the anvil to the stirrup.

Remarkably, the tiny stirrup—the smallest bone in your body—is your ear's most powerful sound amplifier. When the hammer and anvil push on it, the stirrup acts like a piston, pushing rhythmically on the oval window, the membrane that covers the opening to the inner ear. Each time the stirrup pulses against the oval window, it can magnify the force of the hammer and anvil thirty times.

How does such a small bone transmit such a large force? Imagine a well-dressed woman taking a walk across a lush green lawn. With each step, her high heel sinks deep into the spongy turf: all the pressure of her weight is concentrated on that one small spot. That's what the stirrup does. It concentrates all the mechanical pressure of the middle ear on the opening to the inner ear. So when the sound of a buzzing mosquito gets in your ear, its force may be doubled by the resonance in the ear canal, tripled by the lever action of the hammer and anvil, and then multiplied thirty times by the piston action of the stirrup. By the time a sound hits your inner ear, it may have been magnified a total of 180 times.

THE BASILAR MEMBRANE

If you "unrolled" the cochlea, you could see the flexible basilar membrane, which helps sort out high-pitched sounds from low-pitched sounds.



Spelunking through the inner ear

The inner ear is a curious little structure. At one end are the semicircular canals. These three bony loops have nothing to do with hearing: they help you keep your balance. (You can read all about how they work on page 24.) At the other end is the curled-up, pea-sized cochlea, where the processes of real "hearing" take place.

In 1561, Italian anatomist Gabriello Fallopio (who later found the Fallopian tubes in the female reproductive system) identified the cochlea. Anatomists of the time thought that the cochlea was filled with air that vibrated in response to the vibrations that entered the ear. This theory of hearing—that somehow sealed pockets of "implanted air" passed vibrations directly on to the brain—had been around for centuries.

In 1777, however, Philipp Friedrich Meckel proved what some anatomists were coming to suspect. He put an inner ear out on a freezing winter night and, in the morning, cracked it open to find that it was completely filled with frozen liquid. Once Meckel showed that there was liquid in the inner ear, rather than air, the secrets of the cochlea began to open up. Anatomists reluctantly gave up the implanted air theory and began to look more carefully at the anatomy of the inner ear.

Today, scientists love to go spelunking through the inner ear. Like a set of nested dolls hidden one inside the other, the cochlea is full of surprises. "When I finish a session on the microscope," said one researcher, "I feel disoriented, like I've been cave diving." And for good reason.

The cochlea is made up of three fluid-filled tubes rolled up together like a jellyroll. The tube in the center—the central canal—is sandwiched between the vestibular and tympanic canals. If you unroll the cochlea, you can see that these two canals are actually one continuous structure folded back on itself. The vestibular and tympanic canals are filled with a fluid called perilymph, which is almost identical to sea water—a reminder of our ancient, watery beginnings. The central canal contains a different fluid, called endolymph, which is similar to the liquid in your body's cells. These two fluids, which have different chemical compositions and electrical charges, are kept apart by the two thin membranes that define the central canal. On one side is Reissner's membrane, a mere two cells thick; on the other side is the very flexible, very important, basilar membrane.

The basilar membrane spirals all the way through the cochlea. Where it begins, near the oval window, the membrane is thick and stiff. As it gets closer to the center of the cochlea's curl, it's thin and wobbly.

Because of its graduated shape, different parts of the basilar membrane are sensitive to different patterns of vibration. When the stirrup of the middle ear pushes on the inner ear, pulses of energy move through the liquid inside. Essentially, the basilar membrane is "tuned" to react to these pulses of energy at different points along its length. High-pitched sounds set the thick, stiff end moving, and low-pitched sounds get the thin, wobbly end moving. As a result, the basilar membrane sorts out the high and low pitches from the jumble of sounds that you hear.

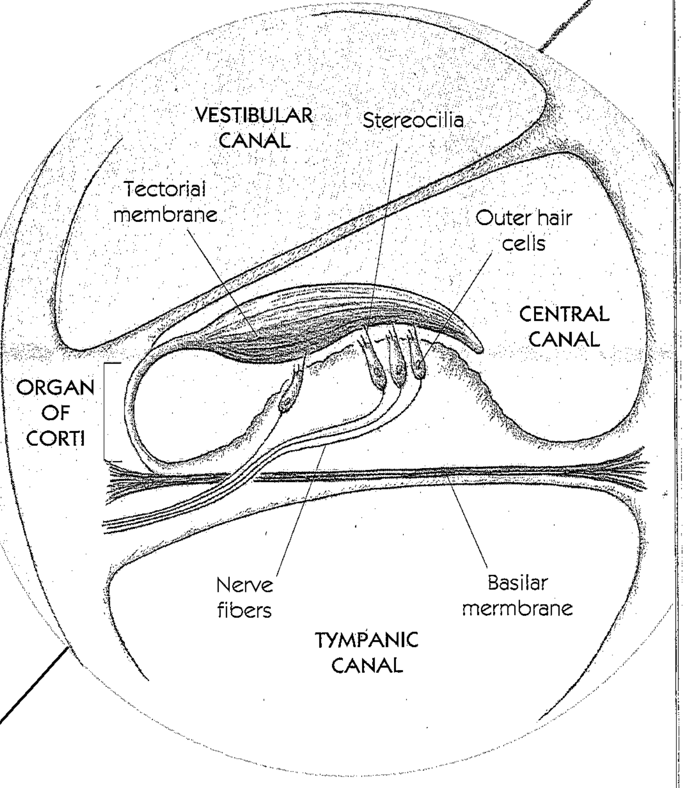
Remarkably, because of its graduated structure, the undulations of the basilar membrane actually reflect the pattern of the original sound wave. The scientist who discovered this amazing phenomenon was Georg von Békésy, who won the 1961 Nobel Prize in Physics for his work. Békésy made his discoveries in the 1920s and 1930s by fashioning artificial cochleas from metal tubes filled with water. He also looked at the inner ears of dozens of different animals, including the elephant, in which this "resonance response" is most visible. (An elephant's ear canal alone is more than eight inches long.)

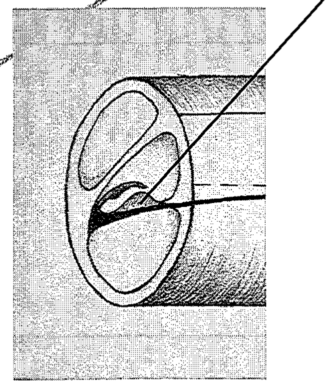
Inside the jelly in the jellyroll

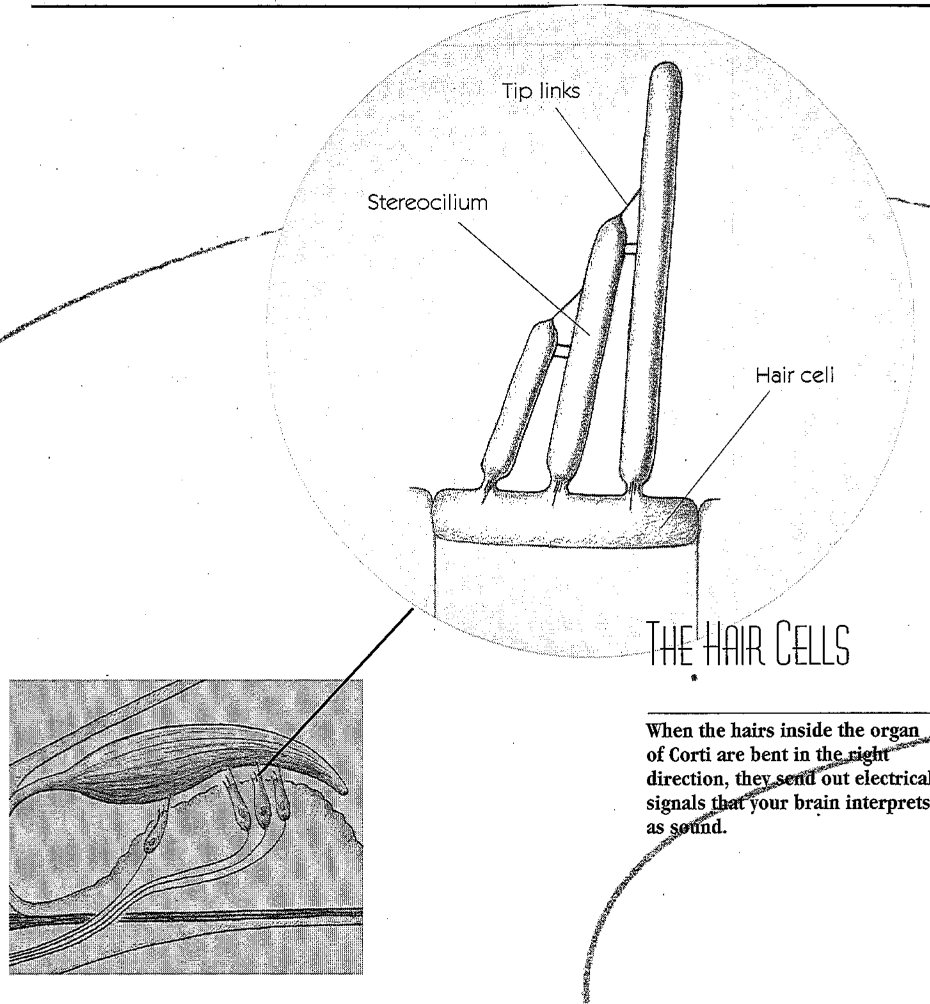
Inside the central canal, embedded in the basilar membrane, is the ear's most elegant and

THE ORGAN OF CORTI

Inside the central canal, sandwiched between the basilar membrane and the tectorial membrane, are the sensory hairs of the organ of Corti.







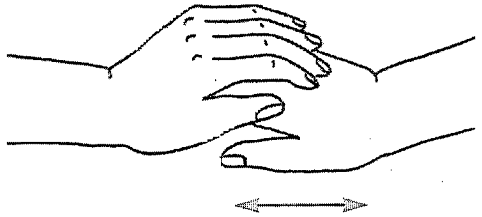
THE HAIR CELLS

When the hairs inside the organ of Corti are bent in the right direction, they send out electrical signals that your brain interprets as sound.

intricate structure: the organ of Corti. In 1851, when Alfonso Corti first identified the mysterious layer of tissue now named for him, he saw rows of delicate, flattened cells that he called "auditory teeth." Looking down through his newfangled compound microscope, Corti thought these elongated cells might wag like little tongues, vibrating in response to the vibrations that entered the ear; stimulating the auditory nerve as they waved. The strange cells Corti saw are indeed responsible for sending sound signals to your brain, but they don't work at all the way Corti imagined.

Inside the organ of Corti are four parallel rows of specialized hair cells—one inner row and three outer rows. Each hair cell (there are sixteen thousand in each ear) is topped by a bundle of about one hundred stiff bristles, called stereocilia, which are arranged in order of height, like school children getting ready for their graduation photo. The bristles are connected to each other by little filaments called tip links. Each tip link attaches the tip of a shorter bristle to the side of its taller neighbor. Pull on one hair, and they all pull on each other.

The tallest of these bristles stick up into a hinged flap of gelatinous tissue called the tectorial membrane. The shorter bristles are also in contact with the tectorial membrane, fitting into grooves along the bottom of the flap. With their bases embedded in the basilar membrane and their tips stuck in the tectorial membrane, the stereocilia are essentially sandwiched in between. When the basilar membrane begins to billow, moving up and down in response to the stimulation of a pressure wave, the bases of the hair cells go along for the ride. But the tips of the hairs get pulled in the opposite direction by the shearing action of the tectorial membrane moving against the basilar membrane.



You can get an idea of how this happens by putting one hand lightly on top of the other, palms down, fingers facing in opposite directions. Hold your elbows away from your body and cup your hands slightly. Now slide your bottom hand back and forth under your top hand. You should be able to see—and feel—your top hand moving in the opposite direction.

Inside your ear, this shearing movement bends the hairs in your hair cells. When the hairs get pulled away from each other, tension on the tip links is thought to open and close molecular "gates," channels through which charged particles may enter. The movement of the charged particles through these channels creates minute bursts of electricity that send signals to your brain.

But at the same time your ear is sending electrical signals to your brain, your brain is also sending electrical signals to your ear. While the nerve cells that connect the inner hair cells to the brain go from the outside in (that is, from the ear to the brain—which makes sense if you're trying to hear something), the nerve cells that connect the outer hair cells do just the opposite: they go from the brain to the ear.

Why? What's your brain trying to tell your ear? Since your basilar membrane vibrates about one hundred times more strongly than it could by simply responding to the energy of a sound wave, researchers think that signals from the brain somehow control the flow of energy from another source—the outer hair cells. Instead of moving passively, like the inner hair cells do, the outer hair cells bound madly up and down whenever they're electrically stimulated. Their mad dance, called "fast motility," is one of the hot new topics in hearing research.

Now that signals from the mosquito's buzz have made their way to the deepest recesses of your inner ear, they've been transformed into bursts of bioelectrical energy. Nerves at the base of each hair cell send these electrical currents whizzing along the auditory nerve to the hearing centers of your brain. Your brain collects these incoming signals from both ears and does its best to make sense of the information. Finally, you hear the sound of that buzzing mosquito.

Smack!

Missed it.

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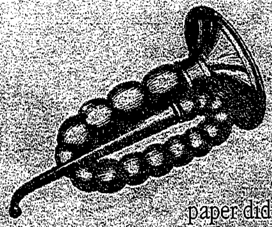
Ear Trumpets & Other Instruments

by Ellen Klages

A century ago, the "hard of hearing" had to use cumbersome ear trumpets. Today, the author's father has a tiny plastic hearing aid that fits inside his ear.



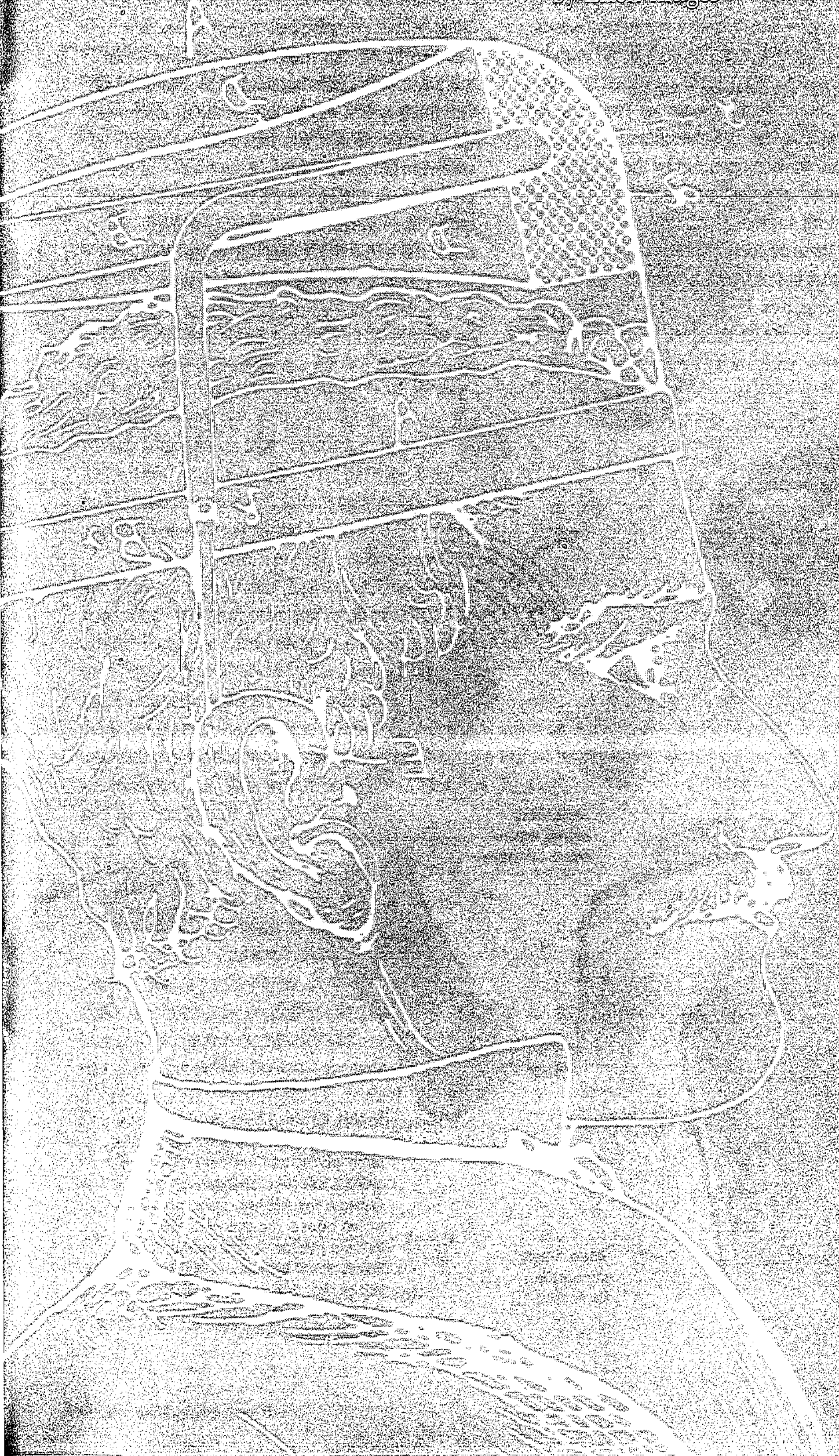
"Is there any meatloaf left?" I asked, walking into the kitchen.

My father was sitting at the table, reading the *Wall Street Journal*. He didn't answer. The paper didn't even jiggle. I asked again, with the same result. Finally I tapped on the paper, and when he put it down I asked him a third time.

"It's in the oven," he said, then added, a little sheepishly, "I had my hearing aid turned down so I wouldn't hear your sister Sally singing along with the TV."

Dad is seventy-one. A few years ago, he began having trouble hearing what other people were saying to him. Accumulated exposure to loud noises, including forty years managing a steel-forging factory, and the declining response to higher-frequency (higher-pitched) sounds that often comes with aging, have left him partially deaf. To compensate, he wears a hearing aid—a tiny piece of flesh-colored plastic in his left ear.

Like all modern hearing aids, Dad's is an electronic device that amplifies the sounds around him, but the earliest hearing aids were merely sound collectors. Anything fan-, cup-, or funnel-shaped, held up to the ear, will "scoop" sounds out of the air and direct them down the ear canal. The larger the scoop, the more sound it collects. If you cup your hand behind your ear, you can increase the amount of sound you hear by a little more than 5 percent. An object with a wide scoop and a small hole at the other end—a seashell or an animal horn—will focus the sounds even better. (See



Nineteenth-century inventors created an amazing array of ear trumpets. There were elegant table models and long, snaking tubes. Giant earpieces were attached to headbands and eyeglasses. Some models were more discreet, like this fashionable ear-trumpet-in-a-hat, circa 1890.