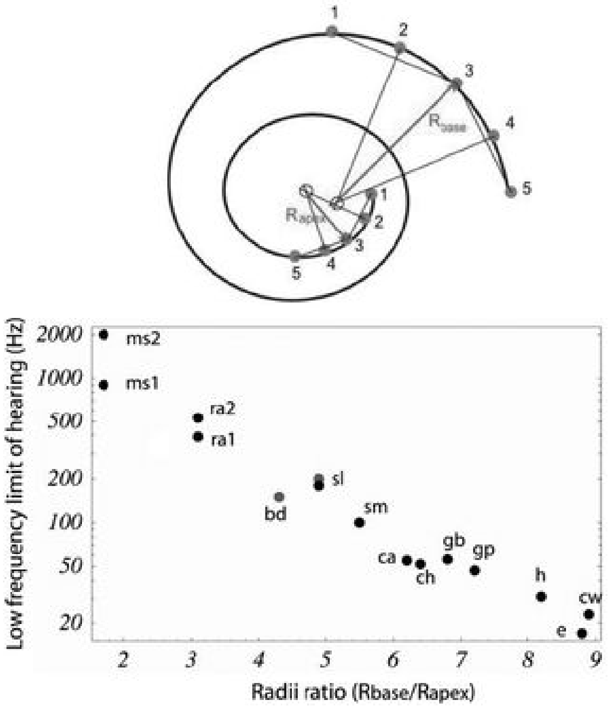
Linking low frequency hearing to the cochlea's curvature



The figure at the top shows how the base and apex radii of the cochlea were determined. The graph at the bottom illustrates the link between the radii ratio and the low frequency hearing limit of a number of species: ms1 and ms2 are two strains of mice; ra1 and ra2 are two species of rat; bd is the bottlenose dolphin; sl is the sea lion; sm is the squirrel monkey; ca is the cat; ch is the chinchilla; gb is the gerbil; gp is the guinea pig; h is the human; e is the elephant; cw is the cow. Courtesy of the Proceedings of the National Academy of Sciences

Shape matters, even in hearing. Specifically, it is the shape of the cochlea — the snail-shell-shaped organ in the inner ear that converts sound waves into nerve impulses that the brain deciphers — which proves to be surprisingly important.

A study published this week in the *Proceedings of the National Academy of Sciences* establishes a direct link between the cochlea's curvature and the low-frequency hearing limit of more than a dozen different mammals.

The relationship will be useful in conservation to estimate the impact that the noises of human activities are having on animals like Siberian tigers, polar bears and marine mammals that won't sit still for hearing tests. It also can provide new information about the hearing of extinct mammals, like mammoths and saber-toothed tigers, and, in so doing, may contribute new insights into how the sense of hearing evolved.

"It turns out that it is the curvature of the cochlea, not its size, that is highly correlated to the low-frequency hearing limit," says Daphne Manoussaki, assistant professor of mathematics at Vanderbilt University, who headed the new study with Richard S. Chadwick, a section chief at the National Institute on Deafness and Other Communication Disorders (one of the National Institutes of Health, or NIH).

Spiral-shaped cochleae are exclusive to mammals. Birds and reptiles generally have plate-like or slightly curved versions of this critical organ, limiting the span of octaves that they can hear. Animals with tightly coiled cochleae tend to have greater hearing ranges, but previous attempts to associate these auditory effects with the physical characteristics of the cochlea have proven unsatisfactory because they did not take a critical acoustic effect into account.

In 2006 Manoussaki and her NIH collaborators published a paper proposing that the helical shape of the cochlea enhances low-frequency sounds through an effect analogous to the well-known "whispering gallery effect" in which soft sounds that travel along curved walls in a large chamber remain loud enough that they can be heard clearly on the opposite side of the room.

When sound waves enter the ear, they strike the eardrum and cause it to vibrate. Tiny bones in the ear amplify and transmit these vibrations to the fluid in the cochlea, creating pressure waves that travel along a narrowing canal in the coiled tube-like organ. The canal is one of two main chambers that are created by an elastic membrane that runs the length of the cochlea. The mechanical properties of this "basilar" membrane vary from very stiff at the broad, outer end to increasingly flexible toward the inner end as the chambers narrow. The basilar membrane's graded properties cause the waves to grow and then die away. Different frequencies peak at different positions along the membrane.

Sensory cells are attached to the basilar membrane and have tufts of tiny hairs called stereocilia that stick up into adjacent structures in the canal. As the basilar membrane moves it tilts the sensory cells, causing the stereocilia to bend. The motion generates electric signals that travel along the auditory nerve to the brain. As a result, the sensory cells near the outer end of the cochlea detect high-pitched sounds, like the notes of a piccolo, while those at the inner end of the spiral detect lower-frequency sounds, like the booming of a bass drum.

This mechanical ordering of response from high to low frequencies works in the same fashion whether the cochlear tube is laid out straight or coiled in a spiral. But Manoussaki's calculations predicted that the spiral shape causes the energy in the low-frequency waves to accumulate against the outside edge of the chamber. This uneven energy distribution, in turn, causes the membrane to move more toward the outer wall of the chamber, enhancing the bending of the stereociliae. The enhancement is strongest at the apex of the spiral, where the lowest frequencies are detected. Manoussaki and her collaborators calculated that the increase in the sound pressure level can be as much as 20 decibels, equivalent to the difference between the aural ambience of a quiet restaurant and a busy street.

"The idea that the cochlea's curvature has a significant effect on hearing has been quite controversial for many years," says Darlene R. Ketten, a senior scientist at Woods Hole Oceanographic Institution and assistant professor at the Harvard Medical School, who participated in the current study. "Curvature was often dismissed or, when examined, the theories were not entirely satisfactory. Now we have a theory that we have confirmed with a number of concrete examples using real ear shapes and hearing abilities."

Ketten provided Manoussaki and her collaborators with high-resolution CT scans of the cochleae of a number of different species of land and marine mammals. Together with her biophysicist colleagues, Manoussaki analyzed these shapes and found that low- frequency hearing limits of species ranging from mice to cats to cows to whales varied in step with the ratio of the radii of curvatures at their cochlea's base to that of its apex. This ratio varies from about two to nine: The larger it is the lower the frequencies that the animal can hear.

"This makes sense because the bigger the ratio, the tighter the spiral is wound and more of the sound wave energy in the low-frequency waves is forced against the cochlea's walls," Manoussaki says.

Animals like mice, which have a radii ratio of about two, can't hear much below 1000 hertz (Hz). Species like cows and elephants, which have a ratio of about nine, hear sounds as low as 20 Hz. The power of this approach is illustrated by the cat, guinea pig and sea lion. The cochlea of the cat is longer than that of the guinea pig, but the guinea pig has a ratio of 7.2 and can hear down to 47 Hz, while the cat, with a smaller ratio of 6.2, has a higher threshold of 55 Hz. Similarly, the sea lion has a basilar membrane three times as long as that of the guinea pig. But its radii ratio is 5.2, lower than either the cat or the guinea pig, and it cannot make out sounds below 180 Hz. (This limit is for the sea lion's hearing in air; under water it can hear down to 200 Hz.)

"What I like about this is that a macroscopic feature of the ear has such a major effect on our hearing," says Manoussaki. "As colleagues have pointed out, so much research today is done at the genetic and cellular level that you don't often see cases like this where simple geometry proves to be so important."

Other contributors to the research are Emilios K. Dimitriadis, National Institute of Biomedical Imaging and Bioengineering; Julie Arruda of Woods Hole Oceanographic Institution and Jennifer T. O'Malley of the Massachusetts Ear and Infirmary.

Source: Vanderbilt University