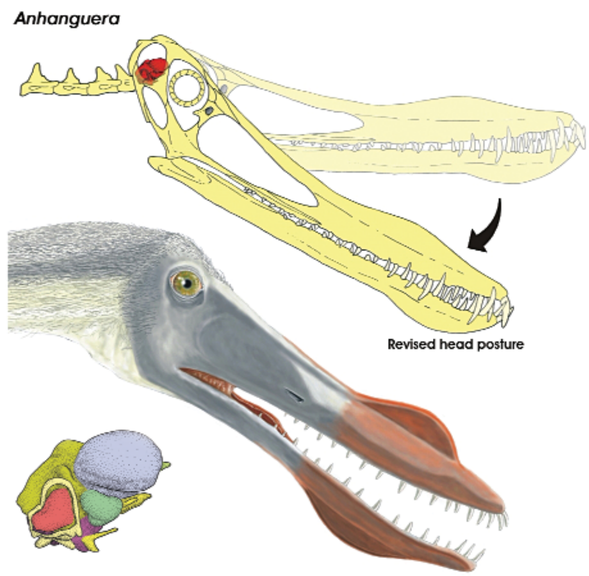
Peering Into Ancient Ears

New views of fossil ears, aided by CT scans, are helping reveal how extinct animals walked, swam, and flew—and perhaps one day even what they heard

St. Paul, Minnesota—Long before birds took to the wing, the skies were ruled by pterosaurs. Some of these reptile kin eventually achieved wingspans of 10 meters, and others sported enormous crests on their head. But how well did they fly? Could they hunt by dive-bombing fish? The ability to peep inside rare fossils and examine their inner ears is now helping paleontologists answer these and similar questions. "We can exploit the structure of the inner ear to tell how an extinct animal may have led its life," says Lawrence Witmer of Ohio University College of Osteopathic Medicine in Athens.

This week in *Nature*, Witmer and colleagues unveil the first detailed look inside the heads of pterosaurs. By using computed tomography (CT) scans, they've shown that the balance organs of pterosaurs are even larger than those of birds. That's strong evidence for agile flying. Also much bigger is the part of the brain that keeps the retinas locked on target, suggesting that pterosaurs were likely more than eagle-eyed at hunting fish and other fast prey. "It's one of the most exciting pieces of work on pterosaurs in recent years," says David Unwin of the Museum of Natural History in Berlin, Germany.

The excitement about inner ears stretches far beyond pterosaurs. Following up on early successes with hominids, paleontologists have been filling CT scanners with a menagerie of fossils. At the annual meeting of the Society of Vertebrate Paleontology (SVP), held here 15 to 18 October, researchers described the inner ears of tiny extinct primates, the oldest known birds, and early whales. These fossilized balance organs, they report, are yielding insights into the behavior and evolution of extinct animals. Eventually, some researchers hope, other structures in the ear may also reveal the range of sounds that ancient animals heard—evidence that may help them deduce how the creatures interacted with their surroundings and with one another.



Cretaceous ace. The large inner ear and related brain region (lower left, red) of this pterosaur implies aerial prowess and a lowered head.

Balancing act

To envision how deftly long-dead animals moved, scientists have traditionally studied limb proportions, muscle attachments, and joints. Limbs, however, are just levers; the inner ear is an animal's guidance system, the mechanism that helps the brain keep its bearings. Three fluid-filled loops, called the semicircular canals, are oriented at right angles to one another. When the head moves, the fluid lags behind and triggers sensory hairs lining the canals. The brain relies on these accelerometers to control the eye and neck muscles, so that a sprinting cheetah can keep its gaze fixed on its prey. "All these mechanisms work in concert," Witmer says. "We can look at the inner ear and get a picture of that."

In living animals, agility tends to go hand in hand with a large-looped semicircular canal. Gazelles, for example, have larger canals relative to their body size than hippos do. Biologists noted this intriguing pattern decades ago by filling the inner ears of dead animals with epoxy and then dissolving the skull. For paleontologists, the disadvantages of demolishing a fossil usually kept the inner ear off limits. Recently, however, CT has given researchers a more detailed, and sometimes unprecedented, look inside the skull (*Science*, 9 June 2000, p. 1728). "It's fair to say that in the last 10 years, there's been a renaissance," says Witmer.

Driving the boom is a flood of comparative data on modern animals. Paleontologists Fred Spoor of University College London and Alan Walker of Pennsylvania State University, University Park, have scanned more than 60 species of primates, along with other mammals. Thanks to a so-called micro CT scanner, the researchers can study specimens whose inner ears would have been too small to see with standard scanners. Initial results confirm that inner ears can distinguish fast, agile primates such as bush babies from slower relatives like lorises.

Armed with such measurements, paleontologists can visualize long-extinct creatures as living, moving animals. In their latest paper, for example, Witmer and colleagues use the scans to infer how pterosaurs held their heads. Their conclusion is based on knowing that one of the three rings, the so-called lateral canal, works best when an animal holds it parallel to the ground. The canals reveal that an advanced pterosaur known as *Anhanguera* typically bent its head down (see figure). The head posture, Unwin says, will help researchers figure out how the crest on the pterosaur's snout affected its flying.

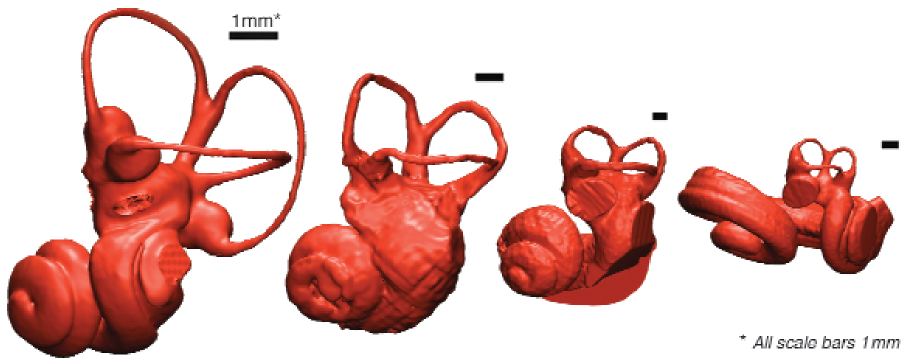
Witmer also showed that a part of the brain that receives input from the balance organs of the ear, called the flocculus, was surprisingly big—even larger than that of modern birds, relative to their body size. That suggests a highly refined sense of equilibrium, he says. The flocculus might have kept tabs on the muscle fibers in the pterosaur's skin-covered wings. Such "smart wings" might have allowed pterosaurs to keep a more stable gaze on fish and other prey, Unwin speculates.

Paleoposture doesn't end with the pterosaurs. Witmer hopes to use CT scans to help answer the controversial question of how sauropods held their massive necks: whether they could raise them to nibble on treetops or whether, as some paleontologists believe, they kept their necks stretched parallel to the ground and grazed on low-lying vegetation.

Paleo-ears can tackle bigger questions as well. Some researchers are using them to study evolutionary transitions: how and when ancient animals changed to adapt to new conditions and new ways of life. When, for example, did our ancestors start to walk gracefully on two legs? In a pioneering CT study in 1994, Spoor and colleagues showed that the modern inner ear of humans appeared in *Homo erectus*, implying modern running and jumping. Examining a more primitive relative, *Australopithecus*, they found that its ears were more like those

CREDIT: ARTWORK BY RYAN RIDGELY AND KYLE MCQUILKIN of great apes, less likely suited for fast, agile two-legged gaits. The results show that humans became full-fledged bipeds some 1.8 million years ago.

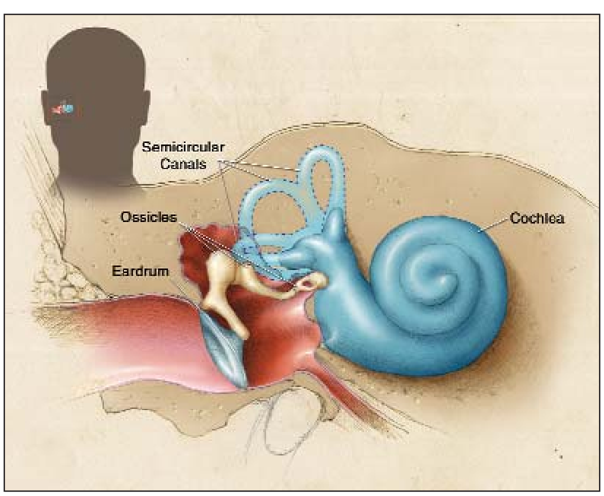
Ears may also say something about how birds evolved from nonavian dinosaurs. At the SVP meeting, Angela Milner of the Natural History Museum in London and Tim Rowe of the University of Texas, Austin, unveiled the first CT scan of the skull of *Archaeopteryx*, the oldest known bird. Although the rest of the skeleton shares features with dinosaurs, Milner and Rowe showed that the skull's semicircular canals are clearly birdlike.



Whorled series. Balance organs of agile bush babies (left) are larger than those of more sluggish whale ancestors. Canals shrank even more relative to body size as whales entered the sea. (Left to right: land-dwelling *Ichthyolestes*, marine *Indocetus*, modern dolphin.)

Also at the meeting, Justin Sipla and Justin Georgi, graduate students at the State University of New York, Stony Brook, reported that they and Spoor had scanned 37 species of modern birds and three of crocodilians, the other closest living relative of dinosaurs. The semicircular canals of birds were larger, relative to body size, than those of crocodilians. Less agile or terrestrial birds, such as the ostrich, had canals like those of crocodilians. Sipla and Georgi hope to use the technique to study the transition from dinosaurs to birds and the evolution of flight.

Similar studies are shedding light on the evolution of marine mammals. Spoor and Hans Thewissen, an anatomist at Northeastern Ohio Universities College of Medicine in Rootstown, have examined the locomotion of whales and their ancestors by scanning semicircular canals of fossil and modern whales. The canals of whales and dolphins are much smaller relative to body size than those of all other living mammals. (The canals of a blue whale are about the same size as ours.) Their compactness makes them less sensitive and may allow cetaceans to swim acrobatically without getting seasick, Thewissen says. The pair reported in the 9 May 2002 issue of *Nature* that the canals shrank quickly and early during the transition back to the sea, implying that the shift was much more rapid than the rest of the skeleton suggests.



Encased. Hidden inside skull bone, ossicles transmit sound; semicircular canals keep the head oriented.

CREDITS: (TOP TO BOTTOM) IMAGE BY F. SPOOR USING VOXEL-MAN; ILLUSTRATION: CAMERON SLAYDEN

Thewissen and his postdoc Sirpa Nummela are also studying how whale ears evolved from those of land mammals to ones that could hear underwater—and eventually use sonar. "This is a very exciting evolutionary story," Thewissen says.

Listening to the past

In using CT scans to study the evolution of hearing, Thewissen and Nummela are pushing the envelope. Some researchers hope to go further—in effect, to use structures in the ear to give fossils hearing tests that would reveal which sound frequencies a living animal could have heard. Making the leap from ear to hearing, however, is harder than it sounds. Researchers know that the acuity of an animal's hearing corresponds crudely to the size of its eardrum. A handful hope to wring more information from the ossicles, tiny bones that transmit sound from the eardrum to the fluid-filled cochlea. The size and shape of the ossicles may reveal whether an animal usually perceived high or low frequencies.

In a pilot project, Mary Silcox of the University of Winnipeg, Canada, has used micro CT to scan 20 contemporary mammals, including primates, rodents, and marsupials, measuring variability in relative lengths of ear ossicles. "If we could figure out what they could hear, we'll get information we never had before," Silcox says. One might be able to estimate the distances over which animals were communicating, she says, because lower frequencies travel farther.

Paleontologists, however, are not sure how much CT scans will teach them about hearing. "The correlation between ossicle size and hearing frequency is extremely tenuous," warns Thewissen, despite repeated attempts to link them. And modeling the acoustic properties of ossicles could prove fruitless without better information about how the nervous system processes the signals they send. "We always struggle with how far we can take this," Witmer says.

CT studies of the anatomy of hearing have yielded at least one intriguing earful. It comes from *Ichthyostega*, a 400-million-year-old four-legged creature famous as a transitional fossil between fish and land vertebrates. While scanning this rare fossil, Jenny Clack of the University of Cambridge, U.K., and colleagues stumbled across some bizarre anatomy that they interpret as a strange kind of ear. The ear is unlike anything else paleontologists or biologists have discovered. The ossicle called the stapes, for example, is extremely thin and platelike, rather than short and blocky as it is in all other known animals. By analogy with the ears of some modern aquatic frogs, the researchers speculate that the ear was suited for underwater hearing—implying that *Ichthyostega* spent more time in the water than paleontologists had believed. Because *Ichthyostega*'s ear is so weird, they argue in the 4 September issue of *Nature* that early land-dwelling animals evolved a wild variety of "experimental" ear types, only one of which has survived, with modifications, to the present day.

Paleontologists are just beginning to flesh out the evolutionary history of the ear. Figuring out the details of ancient ear anatomy will require new fossils as well as better technology. And large suites of comparative data are needed to decipher behavior. With paleontologists mining away, the ear should soon be giving up more of its riches.

–ERIK STOKSTAD