Evolution

All ears about ancient mammals

Anne Weil

The configuration of middle-ear bones in an ancient fossil suggests that specializations suited to eating plants might have influenced how the jaw joint evolved to form the mammal's ear. See p.102

The presence of three delicate bones in the middle ear that are completely separated from the lower jaw can be used to distinguish existing mammals from other vertebrates. This arrangement evolved independently at least three times in mammals, so it is not found in all mammalian fossils. On page 102, Wang *et al.*[1] describe a newly discovered fossil that reveals how these different middle ears evolved into distinct configurations.

The authors named this previously unknown species *Jeholbaatar kielanae*. It was about the size of a vole, and scampered around China about 120 million years ago. It belonged to the longest-lived mammalian lineage, the multituberculates. These typically small-bodied mammals persisted from about 160 million to 34 million years ago, and diverse members of this lineage became common throughout the Northern Hemisphere[2].

Multituberculates might have been so successful because they chewed differently from other mammals. Instead of slicing food into pieces using a vertical biting motion like a cat does, or grinding their food by moving their lower jaw (the mandible) horizontally and sideways like a cow, multituberculates sliced and ground food by drawing their mandible horizontally but backwards. This innovation, 'palinal motion', required specializations of the teeth, jaw joint and musculature. It contributed to the unmatched longevity of the multituberculate lineage, and it facilitated group diversification by enabling multituberculates to use plants as a food source at a time in prehistory when other mammals mainly ate insects or small vertebrates.

Wang and colleagues argue that the adaptation of this chewing approach also drove the evolution of an unusual type of ear. In each independent instance, mammalian middle ears evolved from an ancestral jaw joint. In every case, the articular bone at the back of the mandible and the quadrate bone (which became the incus bone of the middle ear) that it made contact with on the skull retained their connection. These bones shifted slightly internally to form a middle ear together with a bone called the stapes, which was present in mammalian ancestors. Other bones then formed the jaw joint that mammals have today. In transitional stages of this evolutionary process, the connection between the middle ear and the mandible was still present at a middle-ear bone called the malleus, although the extent of this connection was reduced compared with the connection in the ancestral state[3]. Both the jaw and the ear had to function at all stages of the transition. If multituberculates had adopted palinal chewing before the separation of the middle-ear bones from the jaw, how would this arrangement have worked? The tiny but exquisitely preserved middle ear of *Jeholbaatar* (Fig. 1) is completely separated from the jaw, but it provides the beginning of an answer to this question.

It has long been suspected that, in mammalian ancestors, the articular bone and the prearticular bone of the ancestral jaw fused to form the malleus. Fossil discoveries have suggested that a third bone, the surangular, also fused with the articular, at least in some lineages[3,4]. In *Jeholbaatar*, the surangular is present as a separate bone distinguishable along the lateral side of the malleus. The only other animal in which a separate surangular has been described in the ear also shares a second odd trait with *Jeholbaatar*[4]: the position of the incus in the middle ear.

The incus lies flat on top of the malleus in *Jeholbaatar*, in contrast to its position in humans and opossums (*Didelphis*), in which it is positioned posteriorly, behind the malleus. This contact between the incus and the malleus in *Jeholbaatar*, horizontal and parallel to the plane in which the teeth would have met, is what we would expect to see if

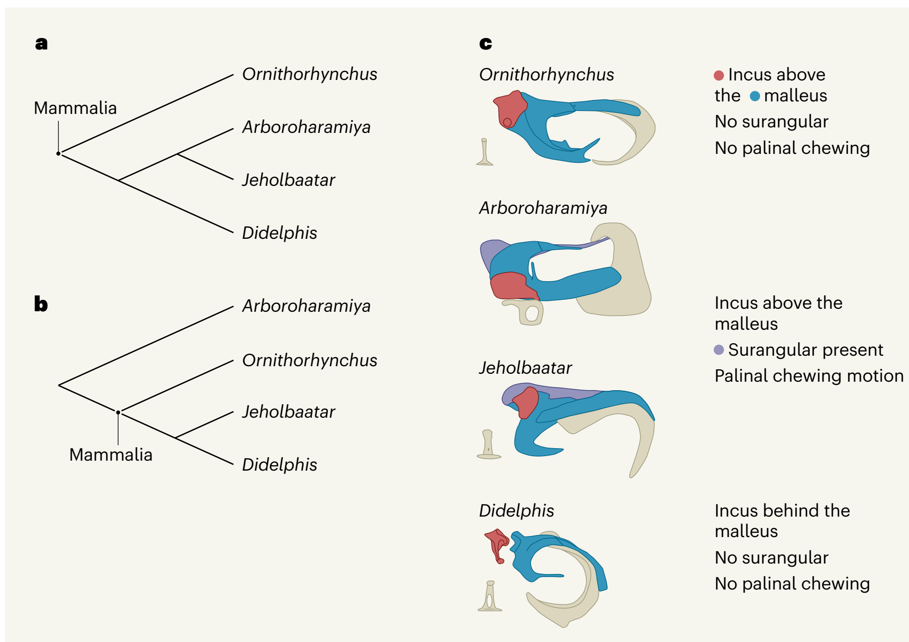

Figure 1 | The evolution of mammalian middle ears. Wang *et al.*[1] report the discovery of a fossil of a previously unknown mammalian species, *Jeholbaatar kielanae*. Its middle ear is similar to that of an extinct animal called *Arboroharamiya*. **a**, This similarity might indicate that *Jeholbaatar* and *Arboroharamiya* should be grouped close together on a mammalian family tree, and suggests that the 'palinal' chewing motion used by *Jeholbaatar* and *Arboroharamiya* has a single origin in a shared ancestor. Also shown in this tree are playtpuses (*Ornithorynchus*) and opossums (*Didelphis*), mammals that don't use palinal chewing and that have middle-ear configurations that are distinct from each other and from *Jeholbaatar* and *Arboroharamiya*. **b**, However, there is some debate about whether *Arboroharamiya* were mammals. If not, as in this tree, then the similar middle ears of *Jeholbaatar* and *Arboroharamiya* evolved independently. **c**, The configurations of the left middle-ear bones of these four creatures are presented as viewed directly from above, with the animal's front to the right. The different configurations of the incus, malleus and surangular bones might reflect the evolution of jaw specializations before bones separated from the jaw to form the ear. (Images based on ref. 1 and not shown to scale.)

palinal chewing had evolved before the middle ear was separate from the jaw[4].

During transitional evolutionary stages, when the malleus was connected to the mandible, palinal jaw movement would have constrained the plane in which the malleus and incus could have been in contact; had the incus been in the more familiar posterior position found in most mammals today, it would have acted as a stop on backward jaw motion. Once palinal motion for chewing was established, increasing the distance the lower jaw moved forwards and backwards on the jaw joint would have made chewing more efficient. Any remaining tether to the ear would have limited the distance that the lower jaw could travel in a single chew, so selection pressure for a fully separate ear and jaw would have been strong, and full separation could have evolved rapidly.

The other animal known to have a surangular in the ear is *Arboroharamiya,* a member of an ancient group known as euharamiyidans with a palinal element to its chewing and an earlier origin than that of multituberculates[4,5]. *Arboroharamiya,* like *Jeholbaatar*, has its incus positioned above the malleus[4,6]. The relationship between euharamiyidans and multituberculates on the evolutionary tree is a matter of lively debate, with some studies, including that of Wang and colleagues, showing them to be closely related within mammals[3,4,7], whereas others place euharamiyidans on a lineage that branched off before the common ancestor of living mammals evolved[8,9]. If the latter scenario is the case, then euharamiyidans would represent a fourth instance of the independent evolution of a fully detached middle ear.

The question of whether the similarities between the ears of *Jeholbaatar* and *Arboroharamiya* reflect a close relationship on the evolutionary tree or independent (convergent) evolution driven by similar chewing adaptations is further complicated by another consideration: the incus of living platypuses (*Ornithorhynchus*) and echidnas, or spiny anteaters (*Tachyglossus*), also lies above the malleus. These mammals belong to a group called monotremes, whose middle ear evolved independently of that of other mammals. Monotremes do not use a palinal chewing motion, and the teeth of fossil monotremes do not suggest that such a motion occurred in early members of that lineage[10]. They might have this arrangement of their incus and malleus for reasons that are entirely different from those explaining the arrangement of these bones in multituberculates or euharamiyidans. Monotremes do not retain a recognizable surangular. If the similarities in the middle ears of *Jeholbaatar* and *Arboroharamiya* reflect the functional similarity in the way the animals chewed, the unfused surangular in *Jeholbaatar* and *Arboroharamiya* might simply reflect the rapidity with which the transition to detachment of the middle ear from the jaw occurred, spurred on by the increased efficiency in food processing that this complete separation would have provided.

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This article was published online on 27 November 2019.

Condensed-matter physics

Electrons in graphene go with the flow

Klaus Ensslin

Scattering between electrons in the material graphene can cause these particles to flow like a viscous liquid. Such flow, which has previously been detected using measurements of electrical resistance, has now been visualized. **See p.75**

Water in a river shows a variety of flow patterns and whirls. Any obstacle in the river, such as a bridge pillar or simply a rough bank, will lead to a distinctive flow pattern. It has been comparatively less obvious how electrons flow in a solid. But on page 75, Sulpizio *et al.*[1] report an experiment in which the flow pattern of electrons in an electrical conductor is imaged.

The electrical resistance of a metal is caused by electrons being scattered from impurities in the material's atomic lattice or from lattice vibrations called phonons. However, it is not affected by electron–electron scattering. When two electrons scatter off each other, their individual momenta are changed by the scattering event. But the total momentum of the two electrons is conserved, as is the total momentum of a sea of electrons in a metal. Therefore, simply measuring the resistance of a metal will not unveil the effects of electron–electron scattering.

To nail down these effects, materials need to be tuned to a regime in which electron–electron scattering is dominant and the

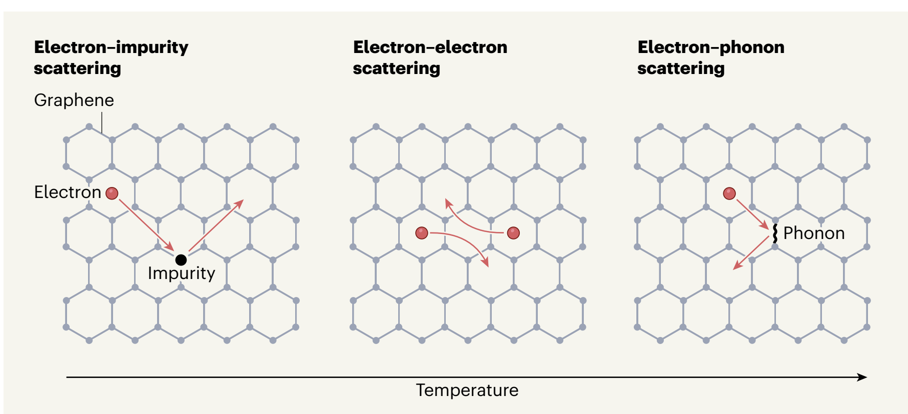

Figure 1 | Electron interactions in graphene. The material graphene consists of a single layer of carbon atoms arranged in a hexagonal lattice. Electrons flowing through graphene can be scattered from impurities (such as foreign atoms in the lattice), from other electrons and from lattice vibrations known as phonons. At low temperatures, electron–impurity scattering dominates. By contrast, at high temperatures, electron–phonon scattering takes over. Sulpizio *et al.*[1] report observations of graphene at intermediate temperatures for which the rate of electron–electron scattering is the largest among all scattering rates.