Palaeontology

Ear pins down evolution of thermoregulation

Stefan Glasauer & Hans Straka

An analysis of fossil specimens of the inner ear helps to refine the timeframe of a key transition in vertebrate evolution – when our mammal-like ancestors began to regulate and maintain a high body temperature. **See p.726**

Unlike the fluctuating body temperatures of some of our relatives, such as reptiles and amphibians, most mammals maintain a relatively stable temperature. The development of this regulatory capacity, called endothermy, is considered a major step in evolution[1]. Araújo *et al.*[2] present on page 726 an analysis of fossil data that offers an innovative way to estimate when endothermy evolved.

To explain the advent of endothermy, a classic paper[3] proposed that this capacity arose when animals acquired the ability to sustain high levels of physical activity as a result of an increase in their aerobic capacity. Simply put, compared with animals that do not thermoregulate, endotherms gained prowess in taking in and using more oxygen to generate energy, thereby also enabling efficient muscle activity for fast movement.

However, moving fast requires efficient maintenance of posture and stability of gaze, and this is where the inner ear comes in. It contains motion sensors that track head movements, providing orientation information similar to the sensor components in a smartphone. However, ear sensors work differently from their digital equivalents.

The ear sensors for rotational movements are the semicircular canals, which exploit the inertia of body fluids. Rotation of the head causes a relative counter-rotation of the fluid (called endolymph) in the inner ear ducts (Fig. 1). This is detected by mechanosensitive hair cells and leads to neuronal signals that are transmitted to specific brain regions. The functional limits of the semicircular canals are determined not only by their dimensions[4], but also by the viscosity of the endolymph. Fluid viscosity decreases rapidly with increasing temperature. Therefore, to evolve a higher body temperature but still maintain the working range for the inner ear's sensing function would require compensatory changes in the size of the semicircular canals (Fig. 1). Thus, to compensate for the endolymph becoming more fluid with increasing temperature, the canal duct would have to become more slender to maintain its dynamic properties.

These considerations inspired Araújo and colleagues to undertake an impressive study that combined palaeontology, complex biomechanics[5] and statistical calculations to infer the body temperatures of various extinct species by examining fossil remains of the animals' inner ears. The work contributes to the solution to part of the endothermy puzzle – namely, the timing of its onset. To establish a relationship between the dimensions of the semicircular canal, its functional limits and body temperature, the authors devised what they term the thermo-motility index (TMI). This is a value grounded in biomechanics, and derived from functionally relevant parameters of the bony dimensions of the semicircular duct system that help to estimate the body temperature (Fig. 1). The present study provides new evidence for the evolutionary onset of endothermy that is based on a quantitative relationship between the properties of motion

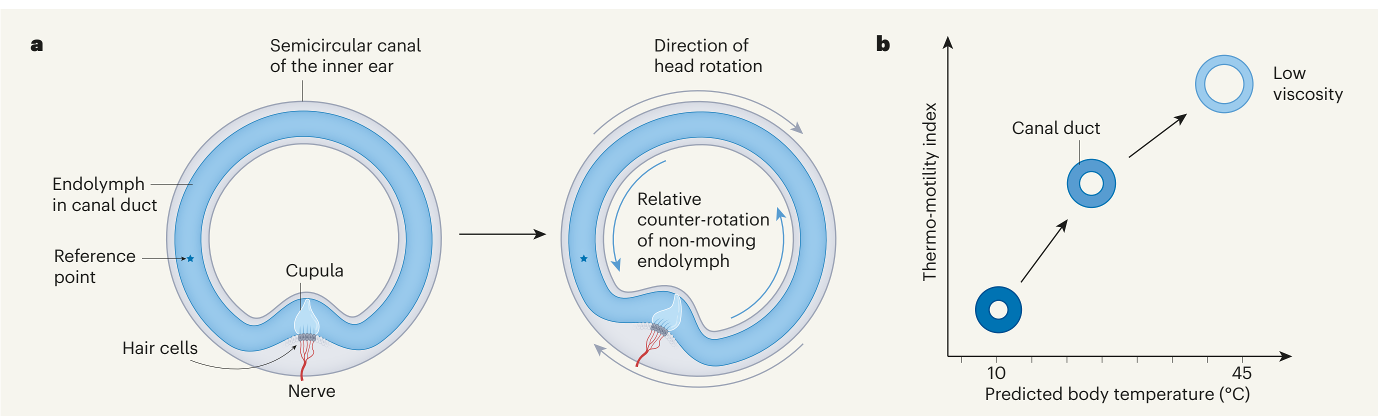

Figure 1 | Inner ear connection to body temperature. a, The horizontal semicircular canal of the mammalian inner ear (view from overhead shown here) acts as a motion sensor to provide information about head rotation. The canal duct contains viscous endolymph fluid, which is inert (as indicated by the marked reference point, which stays in the same position). When the head rotates, the relative position of the endolymph in the canal moves in the opposite direction to that of the head movement. The cupula, a membranous structure inside the canal, is deflected, and this is sensed by hair cells that transmit signals to the brain through nerve fibres. **b**, As the normal body temperature of a species increases, the viscosity of the endolymph decreases (lighter colour). For this motion-sensor system to continue to function within the same limits, such a change in viscosity requires compensatory changes to evolve in the dimensions of the semicircular canals. Araújo *et al.*[2] devised a system of values called the thermo-motility index that offers a way to predict body temperature on the basis of the size and shape of the semicircular canal in fossil samples. This enabled the authors to predict when our mammal-like ancestors first evolved the ability to regulate their body temperature (a property called endothermy). Theoretically, as shown in **b** (graph based on theoretical calculations using information from refs 2, 4, 5), the canal duct would become more slender with increasing body temperature, whereas its overall size would change only slightly. However, the data reported by Araújo *et al.* for present-day species, although indicating a pattern of more-slender ducts at higher temperatures, suggest a rather different picture with regard to changes in the overall canal size – that the size decreases considerably with increasing body temperature. A possible reason for this difference is that, along with a higher body temperature, animals potentially also increased their capacity to move at higher speed, such that the upper functional limits of the system had to be extended, resulting in smaller canals.

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sensors and body temperature, derived from analysis of present-day (extant) species.

To establish whether their prediction system is valid, the authors determined the TMI of more than 200 extant species. They did this using sophisticated analyses of data such as semicircular canal dimensions and body mass to generate a mathematical model relating the TMI to the known body temperatures of these animals. Fossils reveal only the bony dimensions of the canals; however, the dimensions of the canals' membranes are crucial for determining the TMI, and these were estimated using regression models. Although the accuracy of predicting body temperature was relatively poor at the species level, for species grouped into clades, the estimation was fairly good, explaining more than 80% of the variability in the data.

The observed relationship was then used to estimate body-temperature distributions from the TMIs using fossil records of more than 60 extinct species. According to this analysis, the threshold for reaching endothermy, tentatively marked by a 'sudden' increase in the TMI, occurred approximately 230 million years ago. This was in the Late Triassic period during what is known as the Carnian pluvial episode, a period of a large-scale climate change consisting of global warming and increased humidity. The first vertebrates to have thermoregulatory capacity were probably early members of the clade Mammaliamorpha, animals similar in shape to large rodents, and these presumed common ancestors of all extant mammals appeared around the same time as the first dinosaurs[6].

The work by Araújo *et al.* also provides other insights. In extant species, the TMI increased disproportionately more with body temperature than would be expected from just temperature-driven changes in viscosity, thus effectively increasing the sensor's functional limits. The authors interpreted this result as further evidence for the aerobic-capacity model of the evolution of endothermy — a higher body temperature enables increased physical activity, which, in turn, requires motion sensors that can cope with faster movements. In other words, you can only run as fast as your motion sensor can detect the movement.

The evidence pointing to an onset of mammalian endothermy in the Late Triassic is not entirely surprising, given predictions made by other studies using different methods, but the exact timing of this emergence is not undisputed. For example, a study[6] that compiled evidence from various sources, such as the development of hair, signs of nocturnal activity and aspects of bone structure, suggested that mammalian endothermy developed about 20 million years earlier, at the transition between the Permian and Triassic periods.

Although Araújo and colleagues demonstrate systematic changes in the semicircular canals' properties that are related to increases in body temperature, there are limitations to inferring the evolution of endothermy from the bony encasements of a motion sensor. Fossil remains cannot capture the functionally relevant dimensions of the membranous inner ear labyrinth structure, nor the endolymph viscosity or its molecular composition. Araújo *et al.* assumed that the composition of the endolymph remained unchanged during mammalian evolution. By contrast, the viscosity of the endolymph in another group of endothermic animals, birds, is much higher[7], leading Araújo *et al.* to assume that birds and perhaps their dinosaur ancestors compensated for a rise in body temperature in part by changing the biochemical composition of their endolymph.

The most notable caveat regarding determination of the time window for the onset of endothermy is the fact that only three samples of non-mammalian species called probainognathians were included, which, according to Araújo and colleagues' study, were our closest non-endothermic relatives. Although the authors took great care in carrying out extensive mathematical and statistical calculations to show that the observed shift in TMI was probably not a sampling artefact, it is still possible that the estimated onset is off by some tens of millions of years. Given the large variation between TMI and body temperature in extant species, some of the few extinct sample species might have been outliers. Nevertheless, by considering the sensory requirements that accompany movement agility in early mammals, this study offers a refreshing alternative viewpoint that will certainly fuel the discussion[6] about the onset of mammalian endothermy.

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Quantum information

Entanglement provides a key to improved security

Krister Shalm

A cryptographic scheme offers a secure way of exchanging data using a phenomenon called quantum entanglement. The approach relies on special quantum correlations between particles that help to prevent tampering. **See p.682 & p.687**

Every time you buy something online, sensitive information such as your credit-card number is sent to a merchant. To prevent this information from being obtained by a hacker, it is necessary to 'lock' it before sending it. Then, if the merchant has a 'key' corresponding to the one that was used to lock your information, they can unlock it. But how can these keys be distributed in a secure way, so that only you and the merchant have them? In two papers in this issue, Nadlinger *et al.*[1] (page 682) and Zhang *et al.*[2] (page 687) report on a method for using a special property of quantum particles — known as quantum entanglement — to share a secret key without needing to trust the 'courier' that performs the exchange.

In any cryptographic system, each component that needs to be trusted is a possible doorway through which a hacker can enter. And, just as a room with 100 doors is more difficult to guard than a room with only one door, the number of components that need to be trusted determines how challenging it is to protect a cryptographic system from intrusions. Reducing the amount of trust required in such a system is therefore one of the main goals of cryptography.

The oldest method of sharing keys is through a courier, but this requires some assurance that the courier has not been bribed or compromised, and that the keys they carry have not been intercepted in transit. Using couriers for processes such as

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