contents. By comparing the size, composition and abundance of the bromalites with data from fossil skeletal and footprint records, the authors were able to infer the identity, feeding behaviour and relative size and prevalence of the organisms that produced them. On the basis of these interpretations, Qvarnström and colleagues generated food webs from specific time intervals, which track the temporal shifts in the populations and body sizes of both primary consumers (herbivores) and secondary consumers (carnivores).

The methodology of this study is particularly creative, including techniques such as optical microscopy to examine thin sections; chromatographic and mass spectrometric methods to extract and separate plant remains and scanning electron microscopy to analyse them; and synchrotron microtomography to produce 3D images of the internal structures of the samples. The food remains identified in the bromalites included a wide variety of plants and cuticles from invertebrates called arthropods – often with preservation on a level that enabled some basic assignment of specimens to taxonomic groupings – as well as various vertebrate bones, scales and teeth.

The skeletal fossils, footprints and bromalites from sites in Poland provide a series of discrete temporal snapshots that demonstrate a transition from a world with few dinosaurs to one in which they dominated (Fig. 1). This transition occurred against a backdrop of climatic factors that caused shifts in floral communities and might have driven changes in feeding behaviour. The first step in the process was the appearance of small omnivores that were the direct ancestors of early dinosaurs. These eventually evolved to become the early herbivorous and carnivorous dinosaurs that gradually replaced their competitors. The climate-mediated disruption of vegetation communities would favour dinosaurs that were able to feed on a wide variety of food sources, resulting in the emergence of larger and more diverse herbivorous dinosaurs later in the Triassic, and large carnivorous dinosaurs by the start of the Jurassic.

This study advances our understanding of dinosaur diversification and dominance by providing empirical evidence of a mechanism based on random (stochastic) processes. However, the research is limited in its context and scope, and thus should be seen as a starting point for further work. If the replacement of non-dinosaurs with dinosaurs was a consequence of disruptions to the climate, future studies should be able to confirm that these climatic changes happened locally in Poland. Major global climate events of the Late Triassic included an extended humid interval during the Carnian stage (the Carnian Pluvial Episode), and potentially extreme disruptions during the volcanic eruptions that occurred in the Central Atlantic magmatic province in the last part of the Triassic Period. Furthermore, regional changes in the climate could have resulted from plate tectonics – for example, the northward drift of the Polish Basin during the Late Triassic might have altered the area's location in relation to climate zones.

This study is a detailed examination of the fossil record of just one basin. Southern Poland was in the northern part of the Pangaean supercontinent, but the fossil record clearly suggests that dinosaurs first appeared in southern Pangaea, and that they might have diversified before reaching the Northern Hemisphere[7,8]. Using the techniques from this study in other locations would provide a more global context and build a nuanced picture of the connection between Late Triassic environmental disruptions and the ascendancy of the dinosaurs.

Lawrence H. Tanner is in the Department of Biological and Environmental Sciences, Le Moyne College, Syracuse, New York 13214, USA.
e-mail: tannerlh@lemoyne.edu

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Engineering

Liquid metal pumps itself out of artificial vasculature

Michael D. Bartlett

A fresh take on an ancient process for making moulds reverses the usual roles of soft and rigid materials. The resulting process enables complex, 3D channel systems that mimic vasculature to be made in soft biomaterials. **See p.361**

For thousands of years, metal-casting processes have been used to create intricate 3D objects, ranging from ancient crowns and sculptures to modern turbine blades. In conventional casting processes, a 3D template made of a soft sacrificial material, such as wax, is encapsulated in a rigid material and then melted away – revealing an empty space that acts as a 'negative' of the final object to be cast[1]. But what if you wanted to produce spaces in a material that is soft and delicate, and that can't survive the high temperatures typically used to remove the template? On page 361, Sundaram *et al.*[2] introduce a process in which gallium, a metal that is liquid near room temperature, is used as a sacrificial material to generate multiscale 3D channel networks in soft, natural hydrogels such as collagen. This enables soft biomaterials to be engineered to contain channel architectures that approach the complexity of natural tissue structures.

Natural tissues are organized in 3D across multiple length scales, from the subcellular to the organ scale, to regulate biological function. In the field of tissue engineering, fabrication approaches are needed to match this complexity. Artificial vascular networks have previously been made directly through 3D printing biomaterials, or indirectly by encapsulating a sacrificial template in biological matter[3,4]. However, it has proved tremendously challenging to fabricate multiscale 3D arrangements of channels and to reproduce key features accurately at varying length scales. And it is necessary to do this to create environments that can support cells and natural extracellular matrices (the meshworks of proteins and other molecules that surround cells).

One of the challenges when preparing cavities in soft materials, such as tissue and synthetic gels, is that these materials can be distorted by gravity and surface forces – especially at the small scales that are relevant for the structures found in natural tissues[5]. The use of a rigid sacrificial template material increases the resolution of the features that can be made in soft materials. The difficulty is in finding a template that is rigid enough to produce high-resolution features, yet can be removed using conditions that do not damage the soft materials.

Sundaram *et al.* solve this problem using gallium metal. The melting point of gallium is about 30 °C, which means that it can form rigid templates with sharp 3D features, but can be liquified at low temperatures for gentle removal from soft gels. What's more, gallium

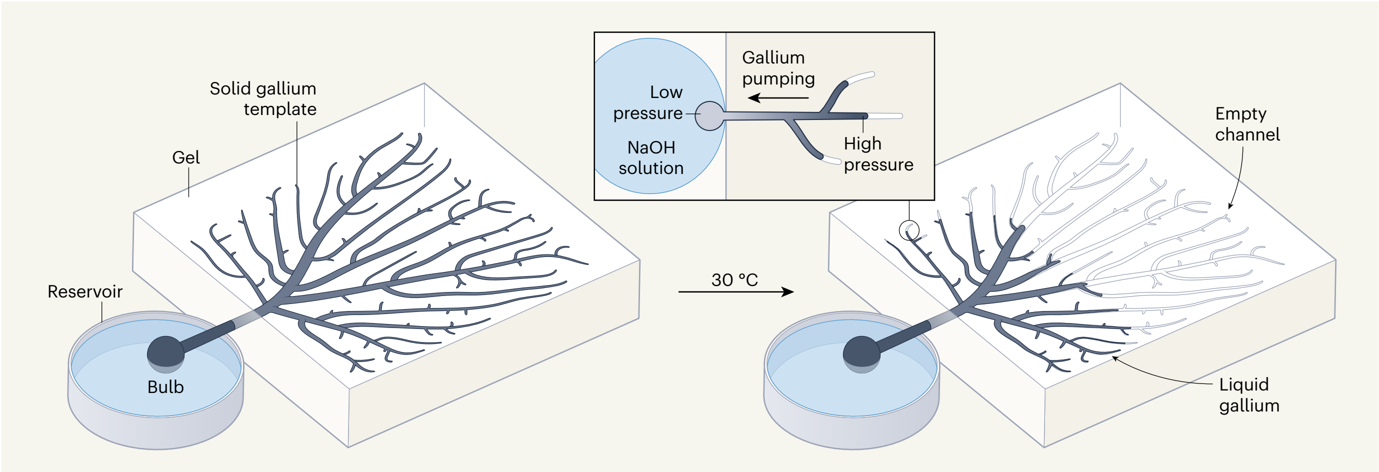

Figure 1 | A method for fabricating complex channel systems in soft materials. In Sundaram and colleagues' method[2], a solid template of a branched channel system, made of gallium metal, is encapsulated in a soft gel. The template connects to a bulb of gallium that projects out of the gel and into a reservoir of sodium hydroxide (NaOH) solution. The gel is warmed to about 30 °C, melting the gallium, and sodium hydroxide solution from the reservoir removes oxide from the surface of the metal. This produces pure liquid gallium, which has a high surface tension. The liquid gallium in the gel is highly curved at the ends of the branches, which creates a large difference between the internal and the external pressure at the liquid surface. The pressure of the liquid gallium in the channels is therefore higher than that in the less-curved bulb in the reservoir. This causes the liquid metal to be pumped out of the gel, producing channels in the shape of the original solid gallium template.

has a thin, stiff shell of gallium oxide on its surface[6], which can be removed using acids or bases, exposing a pure liquid-metal surface. This liquid has remarkably high surface tension, which creates a Laplace pressure — a difference between the internal and the external pressure at the curved surface of the liquid. This pressure, which is inversely proportional to the radius of curvature of the liquid — and therefore to the size of the surrounding channel — can cause the liquid gallium to be pumped through the channel, similar to the way in which water travels up a straw.

The authors cleverly take advantage of the unusual properties of gallium to form channel systems in gels. In their process, a solid gallium template in the shape of a microchannel system is encapsulated in a gel. The template is then warmed and treated with a solution of a base to produce pure liquid gallium. This is connected to an external reservoir of gallium, which is less curved than the liquid gallium in the gel, and therefore has a lower Laplace pressure — causing the liquid metal in the channels to be pumped to the reservoir. This evacuation of the metal produces microchannels in the gel that have the same architecture as the original solid gallium template.

Sundaram *et al.* call this process engineered sacrificial capillary pumps for evacuation (ESCAPE; Fig. 1). Overall, ESCAPE can be thought of as a reversal of conventional millennia-old casting processes, because a hard template is sacrificed to create intricate 3D architectures in soft matter, rather than the other way around.

The authors show that ESCAPE can create complex 3D channel systems in soft biomaterials on which cells can be seeded to grow, as needed for tissue engineering. A wide variety of architectures is demonstrated, including hierarchical vascular networks, overhand knots (see Fig. 2d of the paper[2]), which are particularly challenging to make, and channels that replicate systems known as cardiac bundles, found in heart tissues. The authors could even use ESCAPE to produce surface features in artificial vascular networks to enable cells to seed and grow in alignment with the vessels — a feature of natural systems that is important for vascular health — opening up exciting possibilities for engineered tissues and organs.

One of the challenges with ESCAPE is that a rigid mould is required to form the sacrificial gallium template. The resolution of the final channel system made from biomaterials is ultimately governed by the quality of that first mould. If high-resolution gallium templates could be prepared directly in the future, without being cast from a mould, this would reduce the number of steps and simplify the overall process.

Gallium and its alloys have received considerable attention in the past few years for various applications, including soft electronic devices and robots[7], in which a liquid metal enables the formation of stretchable electrical connections that self-heal; the room-temperature synthesis of atomically thin layers of metal oxides[8], which can form on the surface of a liquid metal; and a range of biomedical applications[9], such as drug-delivery systems and even cancer therapy. By exploiting the low melting point of gallium, and the surface characteristics and low viscosity of gallium's liquid state, Sundaram *et al.* have expanded the possibilities for using this metal across diverse fields.

Metal casting typically invokes images of heavy industry, with red-hot molten metal pouring into moulds. Sundaram and colleagues' work shows that casting processes don't have to be this extreme. Instead, surface tension and melting can be harnessed under mild conditions to produce intricate 3D channel architectures in delicate, soft materials. This paves the way for the fabrication of multiscale, biomaterial structures, a crucial advance towards the engineering of systems that can guide biological functions — no red-hot furnaces required.

Michael D. Bartlett is in the Department of Mechanical Engineering, Soft Materials and Structures Lab and at the Macromolecules Innovation Institute, Virginia Tech, Blacksburg, Virginia 24061, USA.
e-mail: mbartlett@vt.edu

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