the efficient exchange of oxygen and carbon dioxide between the trachea and tissues without the need for a blood system to transport these gases, as is the case for vertebrates. The tracheal system also provides structural support to the insect body and aids in regulating its internal pressure. Hence, the insect trachea functions in a manner similar to that of the blood system of vertebrates.

Previous studies have shown[5,6] that gut muscles secrete a protein, called branchless that promotes tracheal branching (Fig. 1). Branchless belongs to a family of growth factors that binds to cell-surface receptors called FGF receptors (FGFRs), and such receptor-binding ligands can initiate a cascade of intracellular signalling events. The FGF signalling pathway is essential for the formation of new blood vessels in the vasculature of vertebrates and for tracheal development in flies.

The authors noted varying expression levels of FGF ligands between males and females in gut areas that have sexually dimorphic 3D shapes. The authors also observed distinct levels of tracheal branching when comparing males and females (Fig. 1). Blackie *et al.* speculated that male and female gut muscles might secrete differing amounts of the branchless ligand, thereby affecting tracheal branching.

Gut muscle cells have an intrinsic sexual identity that can be genetically altered. Through genetic techniques, the authors masculinized gut muscles of female flies, which resulted in reduced tracheal branching and a 3D gut shape that was more similar to that of males. Thus, the study presents compelling evidence that trachea maintain 3D shape by holding the gut loops together. Crucially, the authors reveal that differential tracheal branching density between males and females is regulated by gut muscles (Fig. 1). Consequently, the study uncovers bidirectional signalling between the gut and tracheal system in *Drosophila*, challenging conventional ideas about how sexually divergent organ shape can be specified.

The prevailing view is that sex-specific differences in organ shape are determined mainly by two factors: intrinsically by sex chromosomes[1] and extrinsically by sex hormones[7]. By identifying inter-organ communication as a sculptor of sexually dimorphic organ shape, this study introduces an unexpected third dimension in organ geometry.

In addition to their stunning discovery of the role of bidirectional inter-organ communication in sex-specific organ shape, the authors report two more surprising findings. First, they identify, using reporters that sense oxygen levels, that disrupting trachea in the specific gut regions of interest does not alter oxygen delivery there. Hence the trachea's main role in this region is to position gut loops, suggesting that it is necessary to consider the diverse roles each organ might have in 3D organ shape. Second, the authors show that instead of the trachea affecting the gut in terms of food transit or ingestion, its role in gut geometry means that the trachea influences the organism's fecundity, starvation resilience and age-induced hyperproliferation of gut cells. This last influence implies that organ shape has a role in tumour suppression. Hence, these data reveal an intriguing but yet to be fully understood connection between sexually dimorphic 3D organ shape and long-term physiological outcomes.

Importantly, this work also provides an alternative perspective from which to consider the following key challenge in organ communication[8]. How do organs discern and respond to molecular signals found across the body (systemically), such as cytokines, amino acids and hormones? The 3D spatial arrangement of organs might explain this because it enables ligands to access specific receptors on target organs on the basis of their proximity. It is possible that changes in organ geometry due to conditions such as cancer, neurodegeneration and obesity disrupt spatial configurations, thus affecting overall human health. This research serves as a framework for investigating organ adjacencies and the physiological consequences of organ-shape alterations.

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Materials chemistry

Self-healing glass made from peptide and water

Silvia Marchesan

A simple peptide has been found to make disordered interactions with water, forming a self-healing glass that can also be used as an adhesive coating. The findings point the way to sustainable alternatives to conventional glass. **See p.368**

Glass has shaped society through the ages like no other material, and its physics and chemistry continue to captivate scientists. The main ingredients are modest – sand, limestone and sodium carbonate – yet these raw materials can be crafted into fine luxury objects. More broadly, the term 'glass' defines a state of matter rather than a chemical composition, referring to any substance that has been cooled to rigidity without becoming crystalline. On page 368, Finkelstein-Zuta *et al.*[1] report the surprising finding that a glass can be made from an organic compound as simple as a tripeptide, which consists of a linear chain of just three amino-acid residues. This new glass has optical properties similar to those of conventional glass, but also has adhesive and self-healing capabilities.

Why do we need to consider alternative ingredients for making glass? After all, the inorganic materials used to make conventional glass are inexpensive and inert – which explains why they have been used for millennia. However, their availability should not be taken for granted. The lack of imported sand following the decline of the Roman Empire caused glass-making in Europe to stall for centuries, for example[2]. More recently, glass manufacturing faced challenges during both World Wars because of problems sourcing the raw materials[3]. Another reason to re-invent glass is that high temperatures are needed to make it, and society urgently needs to transition away from such energy-intensive processes by developing more-sustainable technologies.

Finkelstein-Zuta and colleagues' work stems from research into another class of materials: proteins. Proteins have long fascinated scientists because of the way in which their chemical diversity, intricate and complex structures, and flexible and dynamic nature enable all sorts of function. Proteins are even being developed as a sustainable alternative to widely used commercial materials, such as plastics[4]. But despite intense research efforts and technological advances, many aspects of

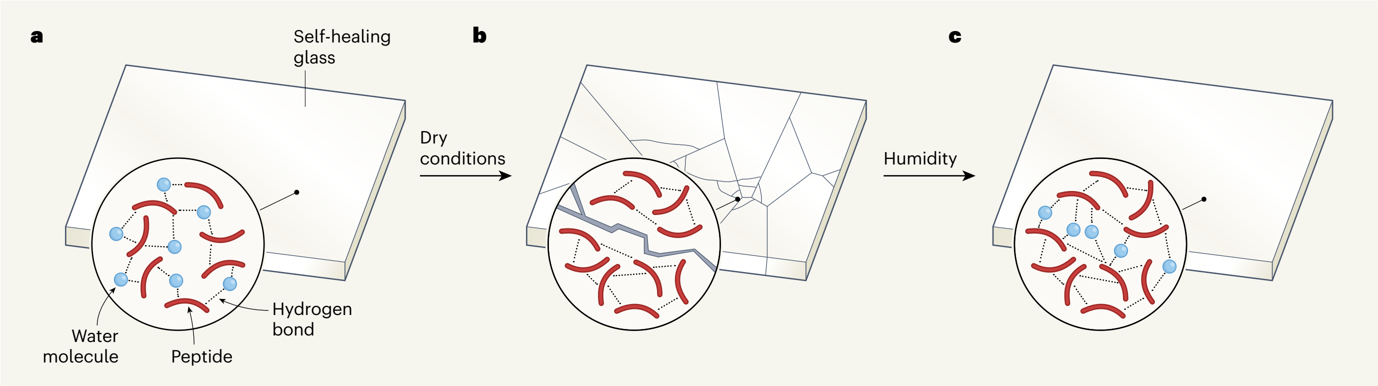

Figure 1 | A disordered network of peptide and water molecules forms a self-healing glass. **a**, Finkelstein-Zuta *et al.*[1] report that a simple peptide molecule forms strong but disordered hydrogen bonds with water, and thereby assembles into a transparent, ductile self-healing glass. **b**, When the glass is exposed to dry conditions, water molecules are lost from the network, and the material becomes brittle and cracked. **c**, Exposure to humid conditions leads to the re-uptake of water molecules and healing of the cracks.

proteins remain as mysterious as the smile of Leonardo da Vinci's *Mona Lisa*.

One strategy for solving these protein mysteries is to take a reductionist approach, similar to that used by Pablo Picasso when he posed a key question in art: what are the simplest elements that can capture the visual essence of a subject? *The Bull* illustrates the answer. In this work of art, Picasso progressively simplifies a realistic drawing of a bull, eventually coming up with a minimal set of lines that would nevertheless still be recognized as a bull. Perhaps short peptides – which can be thought of as simple fragments of proteins – can display some of the essential properties of the more complex parent macromolecules?

In this spirit, researchers from the same group as Finkelstein-Zuta *et al.* previously reported[5] that a dipeptide molecule consisting of two phenylalanine residues maintains the remarkable propensity of a much more complex peptide, amyloid-β, to self-assemble into long, thin and robust nanostructures. Subsequent work[6] showed that simple variants of this dipeptide self-assemble into a range of shapes spanning the nanometre to the macroscopic scales, and that these are more physically robust than proteins, have greater resistance to enzymatic degradation and can have diverse functions. A growing number of researchers now take advantage of the low cost, robustness and chemical diversity of simple amino-acid derivatives to find molecules that self-assemble into biodegradable materials, with technological applications ranging from health care to catalysis and energy harvesting[7].

Finkelstein-Zuta *et al.* now report a further leap forward by showing that a tripeptide consisting of three tyrosine residues self-assembles in a very different way to previously reported systems. Simple evaporation of water from aqueous solutions of the peptide at room temperature leads to the formation of a transparent glass. Moreover, the glass can also serve as an adhesive coating that binds to hydrophilic surfaces – the authors demonstrate that it can be used to glue together two microscope slides, for example.

The high transparency of the glass and its ability to match the refractive index of other glasses are highly promising for applications. For example, it could be used as an adhesive to bond together layers of different materials to make lenses. Multi-layered lenses are highly sought after for high-performance technologies, because each layer can provide a different function, such as scratch resistance and anti-fogging.

One aspect of the tripeptide that is crucial for glass formation is its amphiphilicity – that is, the molecules have mixed hydrophobic and hydrophilic character. This amphiphilicity enables the establishment of a disordered structural network of molecules in which the peptides form strong hydrogen bonds with water (Fig. 1). Moreover, the water molecules make the material ductile. Conversely, when the peptide glass is dehydrated, it becomes brittle and cracks. Remarkably, subsequent exposure of dried, cracked glass to humidity enables it to self-heal. The dynamic properties of the peptide glass are attractive for various applications and suggest that it could be recycled.

Finally, Finkelstein-Zuta *et al.* show that their glass can be used to make simple optical convex lenses with a range of magnification strengths through a 'bottom up' approach – in which water was evaporated from tripeptide solution trapped in cavities coated with a hydrophobic material. This contrasts with the conventional 'top down' method used to make lenses from bulk glass. An attractive feature of the authors' method is that simple adjustment of the solution volume controls the curvature of the lens, and hence the focal length. This suggests diverse applications in the field of modern optics.

Many interesting questions remain. For instance, the number of tyrosine residues in the peptide is crucial: only the tripeptide forms a glass, whereas the di- and tetra-tyrosine peptides, and tyrosine itself, form crystals. Many other examples of innovative materials have been made from tripeptides that contain tyrosine residues[8,9], and in which molecular interactions with water also have a key role[9]. Furthermore, tripeptides have been shown to contain ideal numbers of non-hydrogen atoms to bind biological receptors effectively and thereby exert bioactivity[10]. Could it be that tripeptides also have the optimal range of physico-chemical properties for dynamic binding to targets in applications that go far beyond those involving biomaterials?

Future work should systematically explore variations in the amino-acid sequences, or in the number of residues, of peptides to see how they affect the assembly of the molecules and the properties of the resulting materials. This might reveal interesting trends, such as the effects that emerge when there are even or odd numbers of residues. Such investigations offer ample opportunities for those who wish to navigate these uncharted waters to derive general rules for the design of sustainable peptide-based materials. In the meantime, by mastering the self-organization of minimal peptides and understanding the interactions of these molecules with water, Finkelstein-Zuta and co-workers are transforming this field of research.

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