SOFT MATERIALS

A remedy for thinning hair

Vast beds of 'hair' coat many living systems, and usually exhibit shear-thinning behaviour — their flow resistance lessens with speed. But with geometric tweaks, such beds can also show shear-thickening and asymmetric ratchet-like behaviour.

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The statement "We are 'hairy' on the inside"[1] is a rather unusual way to open a scientific publication. However, it is also undoubtedly true. From the primary cilia in our vascular systems and kidneys to microvilli in our intestines, almost all internal passages in our body are lined with elastic fibres or 'hairs' (Fig. 1). These hairs serve many important functions, ranging from mechanical sensing to chemical exchange and fluid transport. Writing in *Nature Physics*, José Alvarado and colleagues[1] — authors of the paper in question — have described how extensive beds of such soft hairs respond to, and modify, fluid flow in confined passages.

Ironically, the softness of the hair makes this a very hard problem. One must account for the reconfiguration or bending of the hairs in response to the viscous, low Reynolds number flow. This is not entirely understood, although an earlier study of this effect showcased an elegant approach at higher Reynolds numbers[2]. A further complication arises due to confinement effects. In narrow passages, the flow itself depends strongly on the degree to which the hairs bend. Bent hairs are more streamlined and therefore generate less resistance at a given flow speed. Bent hairs also lead to a larger opening for the fluid to flow through unhindered. Thus, the degree of bending has a strong influence on the flow field, which in turn controls the degree of bending.

To characterize this complex coupled system, Alvarado *et al.* devised some clever experiments. These experiments considered flow in the narrow gap between a stationary outer cylinder with a smooth surface and a rotating inner cylinder that was covered with artificial hair beds. The geometry of the hair — its length, spacing and angle relative to the cylinder — was varied systematically. Measurements of the torque required to rotate the inner cylinder at a given speed were translated into an estimate of the flow resistance, or impedance, generated by the hair bed.

This system comprising two concentric rotating cylinders is classical in rheology, the study of flow. It is called Taylor–Couette flow, after Maurice Couette, who developed a similar setup back in the late nineteenth century to measure the viscosity of fluids[3], and Geoffrey Ingram Taylor, who later described the stability of such flows[4]. Of course, the key difference here is that this system is used to characterize the impedance of the hair bed, which depends on complex fluid–structure interactions.

It turns out that the soft hair beds exhibit some interesting rheological properties. In most cases, the hair beds exhibit shear-thinning behaviour. In other words, the flow impedance generated by the hair bed decreases as the cylinder rotation rate increases. This is because faster rotation leads to greater fluid drag on the soft hairs, which causes them to bend more. The resulting streamlined hair shapes and larger opening area lead to a decrease in the effective impedance.

However, if the hairs are angled relative to the cylinder base, their behaviour depends on the direction of the rotation. For flow against the grain, the hair beds exhibit shear thickening. In this case, faster rotation lead to the hairs bending backwards, which leads to an increase in flow resistance (Fig. 1a). For flow with the grain, shear-thinning behaviour persists. This asymmetry also means that angled hair beds can act as rectifiers (or ratchets). In other words, even if the cylinder rotates back and forth in an oscillatory fashion, the hair beds will drive fluid motion along the grain.

Alvarado *et al.* also created a simple and elegant mathematical model to describe their system. Their model assumes that the velocity profile varies linearly in the gap between the outer cylinder and the hair tips, and that there is no flow relative to the hair

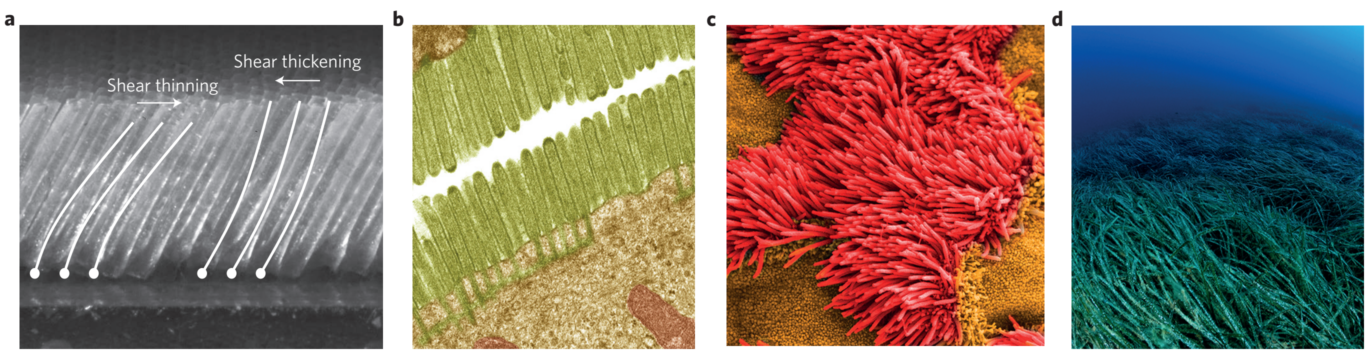

Figure 1 | Artificial and natural hair beds. **a**, Shear-thinning and shear-thickening elastomer bed. **b**, Coloured transmission electron micrograph of intestinal microvilli. **c**, Coloured scanning electron micrograph showing ciliated epithelial cells in lung trachea. **d**, *Posidonia oceanica* meadow off Šušac Island, Croatia. Adapted from ref. 1, Macmillan Publishers Ltd (**a**). Image credits: Steve Gschmeissner/Science Photo Library (**b**); Cultura RM/Alamy Stock Photo (**c**); WaterFrame/Alamy Stock Photo (**d**).

within the bed. This velocity profile is used to calculate the viscous shear stress acting at the top of the hair bed. The shear stress is translated into a horizontal drag force at the hair tips, which causes them to bend.

This model qualitatively reproduces all experimental observations. Perhaps more importantly, it also shows that the effective impedance of the hair bed depends on just two key parameters: an elastoviscous parameter that represents the ratio of the viscous drag causing the hairs to bend and the restoring force due to elasticity; and the ratio of hair length to passage opening, which represents the degree of confinement. Of course, the model does have limitations. For instance, the assumption that there is no flow within the bed breaks down for sparse hairs located far away from each other. The model also exhibits a singularity at the limit where the hair length equals opening size. Nevertheless, it provides an intuitive description of the physical interactions taking place.

Moving forward, the work by Alvarado *et al.* has the potential to inform many biological problems. The rich range of nonlinear flow responses exhibited by soft hair beds (including shear thinning or thickening and rectification) can also be leveraged to design passive microfluidic components such as relief valves, diodes and pumps. The impact of this study is not limited to the microscale either. Extensive beds of flexible filaments are ubiquitous in nature: from surface organelles on the tiniest microbe to grasslands and wetlands spanning miles and miles. ❒

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