Engineers predict how flowing fluid will bend tiny hairs that line blood vessels and intestines

August 21 2017

Credit: Laura Tiitto/public domain

Our bodies are lined on the inside with soft, microscopic carpets of hair, from the grassy extensions on our tastebuds, to fuzzy beds of microvilli in our stomachs, to superfine protein strands throughout our blood vessels. These hairy projections, anchored to soft surfaces, bend and twist with the currents of the fluids they're immersed in.

Now engineers at MIT have found a way to predict how such tiny, soft beds of hair will bend in response to fluid flow. Through experiments and mathematical modeling, they found that, not surprisingly, stiff hairs tend to stay upright in a fluid flow, while more elastic, drooping hairs yield easily to a current.

There is, however, a sweet spot in which hairs, bent at just the right angle, with an elasticity neither too soft nor rigid, can affect the fluid flowing through them. The researchers found that such angled hairs straighten when fluid is flowing against them. In this configuration, the hairs can slow a fluid flow, like a temporarily raised grate.

The results, published this week in the journal *Nature Physics*, may help illuminate the role of hairy surfaces in the body. For instance, the researchers posit that angled hairs in blood vessels and the intestines may bend to protect surrounding tissues from excess fluid flows.

The findings may also help engineers design new microfluidic devices such as hydraulic valves and diodes—small chips that direct the flow of fluid through various channels, via patterns of tiny, angled hairs.

"At very small scales, it's very hard to design things with functionalities that you can switch," says Anette (Peko) Hosoi, professor and associate department head for operations in MIT's Department of Mechanical Engineering. "These angled hairs can be used to make a fluid diode that switches from high resistance to low when fluid flows in one direction versus another."

Hosoi is a co-author on the paper, along with lead author and MIT postdoc José Alvarado, former graduate student Jean Comtet, and

Emmanuel de Langre, a professor in the Department of Mechanics at École Polytechnique.

From cat fur to hairbrushes

"There's been a lot of work done at the large scale, studying fluids like wind flowing past a field of grass or wheat, and how bending or changing the shape of an object affects impedance, or fluid flow," Alvarado says. "But there's been very little work at small scales that can be applicable to biological hairs."

To investigate the behavior of very small hairs in response to flowing fluid, the team fabricated soft beds of hair by laser-cutting tiny holes in sheets of acrylic, then filled the holes with liquid polymer. Once solidified, the researchers removed the polymer hair beds from the acrylic molds.

In this way, the team fabricated multiple beds of hair, each about the size of a small Post-it note. For each bed, the researchers altered the density, angle, and elasticity of the hairs.

"The densest ones are comparable to short-hair cat fur, and the lowest are something like metal hairbrushes," Alvarado says.

The team then studied the way hairs responded to flowing fluid, by placing each bed in a rheometer—an instrument consisting of one cylinder within another. Scientists typically fill the space between cylinders with a liquid, then rotate the inner cylinder and measure the torque generated when the liquid drags the outer cylinder along. Scientists can then use this measured torque to calculate the liquid's viscosity.

For their experiments, Alvarado and Hosoi lined the rheometer's inner cylinder with each hair bed and filled the space between cylinders with a viscous, honey-like oil. The team then measured the torque generated, as well as how fast the inner cylinder was spinning. From these measurements, the team calculated the impedance, or resistance to flow, created by the hairs.

"What is surprising is what happened with angled hairs," Alvarado says. "We saw a difference in impedance depending on if fluid was flowing with or against the grain. Basically, hairs were changing shape, and changing the flow around them."

"Interesting physics"

To study this further, the team, led by Comtet, developed a mathematical model to characterize the behavior of soft hair beds in the presence of a flowing fluid. The researchers worked out a formula that takes into account variables such as the velocity of a fluid and the dimensions of the hair, to calculate rescaled velocity—a parameter that describes the velocity of a fluid versus the elasticity of an object within that fluid.

They found that if the rescaled velocity is too low, hairs are relatively resistant to flow and bend only slightly in response. If the rescaled velocity is too high, hairs are easily bent or deformed in fluid flow. But right in between, as Alvarado says, "interesting physics start to happen."

In this regime, a hair with a certain angle or elasticity exhibits an "asymmetric drag response" and will only straighten out if the fluid is flowing against the grain, slowing the fluid down. A fluid flowing from almost any other direction will leave the angled hairs—and the fluid's velocity—unperturbed.

This new model, Alvarado says, can help engineers design microfluidic devices, lined with angled hairs, that passively direct the flow of fluids across a chip.

Hosoi says that microfluidic devices such as hydraulic diodes are one essential piece to developing complex hydraulic systems that can ultimately do real work.

"Computers and cellphones were made possible because of the invention of cheap, solid-state, small-scale electronics," Hosoi says. "On hydraulic systems, we have not seen that kind of revolution because all the components are complex in themselves. If you can make small, cheap fluid pumps, diodes, valves, and resistors, then you should be able to unleash the same complexity we see in electronic systems, in hydraulic systems. Now the solid-state hydraulic diode's been figured out."

More information: Nonlinear flow response of soft hair beds, *Nature Physics* (2017). DOI: 10.1038/nphys4225

Provided by Massachusetts Institute of Technology