Unraveling threads of bizarre hagfish's explosive slime

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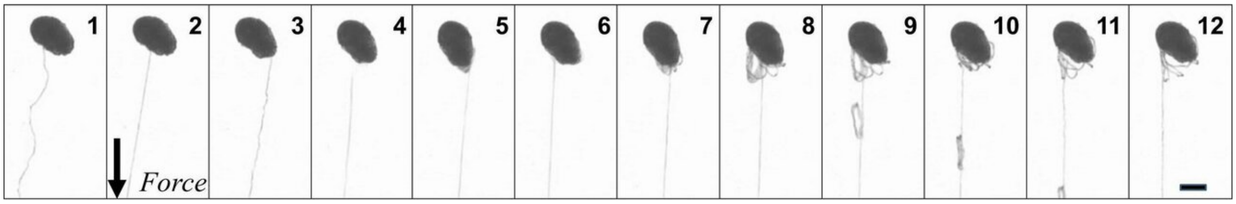

As long as a free end gets stuck on something, and some force from moving water or struggling fish pulls in the opposite direction, tiny skeins of thread produced by hagfish can unspool fast enough to make an enormous amount of protective slime. Credit: Jean-Luc Thiffeault

Hundreds of meters deep in the dark of the ocean, a shark glides toward what seems like a meal. It's kind of ugly, eel-like and not particularly meaty, but still probably food. So the shark strikes.

This is where the interaction of biology and physics gets mysterious—just as the shark finds its dinner interrupted by a cloud of protective slime that appeared out of nowhere around an otherwise placid hagfish.

Jean-Luc Thiffeault, a University of Wisconsin-Madison math professor, and collaborators Randy Ewoldt and Gaurav Chaudhary of the University of Illinois have modeled the hagfish's gag-inducing defense mechanism mathematically, publishing their work today in the *Journal of the Royal Society Interface*.

The ocean-dwelling hagfish is unique for all the strangest reasons. It has a skull, but no spine or jaw. Its skin hangs loose on its body, attached only along the back. Its teeth and fins are primitive, underdeveloped structures best described with qualifiers—"tooth-like" and "fin-like."

But it has an amazing trick up that creepy, loose sleeve of skin: In the blink of an eye (or flash of attacking tail and teeth) the hagfish can produce many times its own body's volume in slime. The goop is so thick and fibrous, predators have little choice but to spit out the hagfish and try to clear their mouths."The mouth of the shark is immediately chock full of this gel," Thiffeault says. "In fact, it often kills them, because it clogs their gills."

The gel is a tangled network of microscopic, seawater-trapping threads unspooled from balls of the stuff ejected from glands along the hagfish's skin. These "skeins" are just 100 millionths of a meter in diameter (twice the width of a human hair), but so densely coiled that they can contain as much as 15 centimeters of thread.Curious scientists have looked at the unraveling before, putting the skeins in salt water to see how long it took them to come apart.

"The hagfish does it in less than half a second, but it took hours of soaking for the threads to loosen up in experiments," says Thiffeault, whose research is focused on fluid dynamics and mixing. "Until they stirred the water, and it happened faster. The stirring was the thing."

The slime modelers set out to see if math could tell them whether the forces of the turbulent water of a bite-and-shake attack were enough to unspool the skeins and make the slime, or if another mechanism—like a chemical reaction providing some pop to the skein—was required.

Ewoldt, a mechanical engineering professor, and his graduate student Chaudhary began unraveling skeins under microscopes, watching the process as loose ends of thread stuck to the tip of a moving syringe and trailing lengths spun out from the ball.

"Our model hinges on an idea of a small piece that's initially dangling out, and then a piece that's being pulled away," says Thiffeault. "Think of it as a roll of tape. To start pulling tape from a new roll, you may have to hunt for the end and pick it loose with your fingernail. But if there's already a free end, it's easy to catch it with something and get going."

Unrolling requires a big enough difference between the drag on the free end and an opposing push on the skein—a ratio larger than a tipping point the researchers refer to informally as the "peeling number"—to free more thread.

"That's unlikely to happen if the whole thing is moving freely in water," says Thiffeault. "The main conclusion of our model is we think the mechanism relies on the threads getting caught on something else—other threads, all the surfaces on the inside of a predator's mouth, pretty much anything—and it's from there it can really be explosive."

It doesn't even have to be a single snag.

"Biology being the way it is, it doesn't have to be exact. Things get to be messy," says Thiffeault. "That leading bit of thread can get caught a little bit, then slip, then get caught again. As long as it's happening to enough skeins, it's pretty fast that you're in the slime."

The skeins may get a boost from mucins, proteins found in mucus that could speed the breakup of packed thread, "but those kinds of things would just help the hydrodynamics," says Thiffeault, who once calculated the extent to which swimming marine life mix entire oceans with their fins and flippers.

"It's just hard to imagine there's another process other than hydrodynamic flow that can lead to these timescales, that burst of slime," he says. "When the shark bites down, that does create turbulence. That creates faster flows, the sorts of things that provide the seed for these things to happen. Nothing is going to happen as nicely as in our model—which is more of a good start for anyone who wants to take more measurements—but our model shows the physical forces play the biggest role."

The hydrodynamics of hagfish slime is not just a curiosity. Understanding the formation and behavior of gels is a standing issue in many biological processes and similar industrial and medical applications."

One of the things we'd love to work on in the future is the network of threads. I love thinking about modeling materials as big random collections of threads," Thiffeault says. "A simple model of entangled threads may help us see how that network determines the macroscopic properties of a lot of different, interesting materials."

More information: Unraveling hagfish slime, *Journal of the Royal Society Interface*, rsif.royalsocietypublishing.or … .1098/rsif.2018.0710

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