Green dye sheds light on locomotion in the ocean

MIT/WHOI graduate student Kelly Rakow Sutherland emerges from a nighttime scuba dive off Panama where she videotaped the movements of transparent gelatinous marine life called salps.

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The boat loaded, we push off from shore. We are headed out for a nighttime blue-water scuba dive in search of salps off the Pacific coast of Panama.

Salps are transparent, barrel-shaped organisms, ranging in size from about 0.5 to 5 inches long, that live in all oceans except the Arctic. Yet few people have ever seen one because they are adapted to live far from shore. This evening's objective is to videotape swimming salps using a harmless, bright green fluorescent dye to better see how they move and feed.

Salps swim and eat by rhythmic pulses. Each pulse draws seawater in through a siphon opening at the front end of the animal. Then the salp contracts muscle bands, and the water shoots out another siphon at its rear end, producing a jet that propels the animal forward. In the process, food particles in the water (mostly tiny plankton) are caught on a mesh of mucus strands inside the salp's mostly hollow body.

In other words, this simple pumping simultaneously controls both feeding and swimming. It also formed the basis of the research for my Ph.D. dissertation. The animals get energy from food and expend energy to move. If these essential functions are coupled, how do various species of salps balance their energy resources?

There are about 40 species of salps with a wide diversity of body shapes; perhaps some species are good at filtering lots of seawater through their feeding mesh at the expense of being good swimmers, and vice versa. Since no one had explicitly considered these trade-offs before, I wasn't sure what I'd find out.

This seemingly esoteric question has ramifications for the marine food web and even Earth's climate. Salps filter huge amounts of phytoplankton, tiny photosynthetic marine plants that take up carbon dioxide in waters near the ocean surface and convert it into organic carbon. The salps package this carbon-rich material into dense, fast-sinking fecal pellets that provide carbon for other organisms that live deep below the surface. If those pellets sink deep enough, carbon is removed from the surface, where it might otherwise exchange with the atmosphere, and instead is sent into the depths, potentially for thousands of years. People today talk about sequestering the excess carbon dioxide that has built up in our atmosphere in the oceans; salps have been facilitating this process for millions of years.

Photo by Stephan Bullard, University of Hartford

Into the black

Several years of work and collaboration have led up to tonight's dive. Research objectives aside, though, it is just plain exciting to be out here, the warm wind blowing against our skin, the expanse of stars over our heads, and the anticipation of diving below the inky surface of the ocean.

The Liquid Jungle Lab, where we are doing this work tonight, is on a small forested island off Panama's Pacific coast. The lab was conceived and built by Italian businessman Jean Pigozzi, who has a passion for science, technology, and conservation. This spot is not only beautiful, it turns out to be ideal for studying oceanic plankton such as salps, which are transported close to shore by local currents.

Dan Martin, a marine biologist at the University of South Alabama, is our safety diver tonight. He will float near our central downline, which is attached to a surface float and to the boat. He will keep a watchful eye on me and marine biologist David Kushner. David runs the Kelp Forest Monitoring Program at Channel Islands National Park in California. I am extremely lucky to have him dive with me.

We will be secured to tethers attached to the same downline, but any time you're on a science dive, a working dive, you're not really focused on your equipment or where you are. You're focused on doing the task. You're in a dark, limitless space, and you can end up drifting up or sinking way down. So it's important to have someone keep an eye on you.

Once beneath the surface, the myriad forms of plankton stand out against the dark background, illuminated by our flashlights. It's challenging to find salps at night. It's like walking around with a flashlight at night—you only see what's in the flashlight beam. You can't look around 360 degrees and see things.

The dye is cast

We are doing this work at night because of the fluorescent dye. We need the darkness to get good contrast. During the day, there's just too much ambient light to see the dye.

When we find a salp, we organize ourselves and then start filming. David squirts the bright green dye near the front end of the salp, which sucks it up and ejects it out its back end. With an underwater video camera, I capture the motion of the dye. It illuminates the movement of the water, which is caused by the movement of the salp.

We usually know if we nailed it. As a videographer, you definitely get this feeling of, "Oh yeah, that was a good one!" But you don't know for certain, because it happens pretty fast. For now, we collect as much footage as we can to increase our odds of having a couple of good shots.

The work we are doing tonight represents one aspect of my research. Using dye to visualize the wakes of swimming salps provides insights into their swimming efficiency. The patterns illuminated by the dye indicate how fast the water moves, how coherent the flow is, and whether or not vortex rings form in the wake. Vortex rings are swirling pulses of ejected water. Made visible by the dye, they look like smoke rings. Previous research has shown that in other jet-propelled swimmers such as squid and jellyfish, vortex rings are associated with efficient swimming.

Back at the lab on shore, I have been taking similar measurements of swimming salps using a method called particle image velocimetry. In PIV, a laser sheet lights up particles in a transparent tank. As a salp swims, it moves the particles, which are illuminated by the laser light. By filming the particle motion with a high-definition camera and then tracking how groups of particles move over time, I can precisely measure the speed and structure of the swimming wake produced by a salp. PIV is a relatively established technique, but no one has ever used it with salps before.

Using dye to observe salp movements in their natural environment isn't completely new; my advisor, WHOI marine biologist Larry Madin, used the technique years ago. But I thought coupling PIV experiments with in-the-field dye work would give me insights neither method alone would. The lab PIV measurements are more quantitative, yielding the exact speed of a salp and its jet wake, but the field-based measurements provide a sort of ground truth; they tell me that what I'm seeing in the lab is a reflection of what's actually happening out there in the oceans.

Pegea confoederata

Scientists squirt green dye near a salp.

Salp sucks dyed water into its front end.

Salp expels a jet of green water out its back end.

The jets propel the salp through the ocean.

Kelly Rakow Sutherland, WHOI

Solitary or aggregate

Salps have an unusual life cycle that alternates between two forms. Solitary salps use asexual budding to produce the next generation, which emerges from the parent salp as a chain, or aggregate, of many individual salps. In turn, members of an aggregate produce the next generation of solitaries by sexual reproduction.

The individuals in a chain look different from their solitary parent, and they are also connected to their siblings. Depending on the species, individuals in an aggregate fit together in different ways to form different shapes. Some aggregates are very streamlined, while others are more clunky looking.

Our goal tonight is to capture video from three species representing the range of body shapes and swimming styles. The results of this work, including tonight's dive, are showing something novel and fascinating about the different salp forms.

It turns out that the fastest and most streamlined species I tested, *Weelia*, is not very hydrodynamically efficient. They moved fast, but not as fast as the water they ejected, so they wasted energy. Another species, *Pegea*, moved more slowly but was more hydrodynamically efficient; they moved at a speed closer to the speed of the water they expelled.

All of the species I investigated produced vortex rings. In the more efficient swimmers, all of the water in their wakes ended up in vortex rings, but in the fast-but-less-efficient swimmers, much of the water in their wakes ended up in a straight stream, or trailing jet, behind a smaller vortex ring.

But when it came to feeding rates, after I adjusted for the size differences between species, I found that all the salps pumped food through their bodies at similar rates. Although swimming and eating are controlled by the same body movements, more efficient swimming is not related to more efficient feeding.

It appears that salps have evolved different swimming strategies that may allow them to reproduce better or to escape from predators. Thus, individual species may find niches in the vast, seemingly homogeneous open ocean. Fast-swimming species may be able to move farther up, down, and across the ocean. The movements of slow swimmers are more limited, but they are more hydrodynamically efficient.

Beyond helping us better understand how organisms perform in their environments, investigations of animal form and function may one day help us achieve engineering goals. Though it's unrealistic to say, "We're going to make an underwater vehicle that's like a salp," a whole field of study called biomimetics is devoted to learning what we can from successful evolutionary designs. That's an interesting application that I might follow up on in years to come.

In the moment though, we are simply thrilled to be diving in the tropical Pacific Ocean and observing these fascinating animals firsthand. We emerge from the dive chatting excitedly about the animals we've seen and the video we've collected. As we head back, tired from the dive, Dan, David, and I grow quiet, in awe of the vast sky above and the bioluminescence in the wake of our boat. The only other light is from the laboratory on the wooded shore ahead.

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See video at whoi.edu/oceanus/salps