

Research news

Examining dolphin hydrodynamics provides clues to calf-loss during tuna fishing

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A combination of mathematical modeling and direct observation of the swimming behavior of dolphin mother-calf pairs has shown how the calf can gain much of the energy required for swimming if it is positioned correctly relative to the mother, a situation that may be disrupted during the chases that result from tuna-fishing practices.

Anyone who has bought a can of 'dolphin-friendly' tuna knows that dolphins can be unintended victims of the tuna-fishing industry. Now, a mathematical model shows that dolphin calves can gain up to 90% of the energy required for swimming if they position themselves correctly relative to their mothers, but that the calves are in danger of being lost if this positioning breaks down [1]. As observations of dolphins in the wild support the model (see 'The bottom line' box for a summary of the findings), the new work starts to give a possible explanation why dolphin numbers remain at unnaturally low levels despite changes in the tuna-fishing industry aimed at protecting dolphin populations.

A brief history of tuna and dolphins

During the 1970s an estimated 350,000 dolphins were killed each year as an unintended but inevitable by-catch of the tuna fishing in the eastern tropical Pacific Ocean (see the 'Background' box). This occurred because

between 1959 and 1963 the tuna-fishing fleet switched from pole and line fishing to a technique using vast 'purse seine' nets. Dolphins are caught because fishermen have known for a long time that tuna gather beneath schools of dolphins and very often

seabirds congregate overhead - if you want to catch tuna, look for dolphins.

Purse-seine fisheries involve a fast moving boat and a helicopter that search for the telltale signs of seabirds and dolphins. On arriving near a school of dolphins the main boat

The bottom line

- A mathematical analysis of the forces between adult dolphins and their calves indicates that if a young calf is in the right position it can gain up to 90% of the force needed to swim from the adult, in an ideal world.
- In a more realistic and detailed model, the calf may receive up to 60% of the thrust from its mother, but it must be very close to her side to receive this benefit.
- In real-life situations calves do 'draft' alongside their mothers in the positions the model shows to be optimal.
- Methods of fishing that involve chasing dolphins may run the risk of separating adults and calves, perhaps explaining why the introduction of dolphin-friendly tuna-fishing methods has not led to a restoration of dolphin numbers.

Background

- **Purse-seine fishing** for tuna involves the use of an enormous net that is dragged around entire schools of fish and then drawn closed with a 'purse-string'.
- Dolphins tend to school relatively high in the water, above schools of tuna, so dolphins become accidental **by-catch** when schools of tuna are trapped by a purse seine.
- Dolphin calves do not have the muscle power to swim as fast as their mothers, so they **draft** alongside, swimming very close by but not in contact, in positions that optimize their use of the mother's **slipstream**.

launches four to six speedboats that operate like sheep dogs, chasing the dolphins so that they are kept together while the main boat encircles them with a one-mile long, 400-foot deep curtain of net, the top edge of which is held on the surface by floats (Figure 1). The chase tends to last between 15 and 30 minutes, but occasionally extends to up to an hour. Once the circle is complete, the fishermen pull a rope that draws the bottom of the net together. This captures the tuna, but also encloses the dolphins. Without assistance, the dolphins can get caught up in the net and, unable to reach the surface, drown.

Since the 1980s various changes in fishing procedures have reduced dolphin mortality. Before pulling the net in, the main boat turns and, because of the way it is constructed, the circular net forms a finger-like shoot opposite the large boat. The speedboats head for this part of the net and hold it open so that the dolphins can swim out. Given that dolphins experience this procedure fairly frequently, they appear to learn what to do. Their escape is helped by the fact that the net in this area is made of a very fine mesh so that they don't get caught, and divers swim inside the net actively pulling some of the stragglers out to the open ocean.

While the effort given to helping dolphins escape has cut deaths significantly, conservationists have been puzzled to note that dolphin numbers are nevertheless failing to recover. One possible clue to the problem came when researchers examining data collected by observers placed with the tuna fleet found that more lactating mothers were killed within the net than nursing calves. Elizabeth Edwards, a marine biologist working for the National Marine Fisheries Service in San Diego, USA, notes that "70-80% of lactating females killed were not killed with a calf, and the findings were consistent over several years". Edwards and her colleagues started looking to see whether calves could become separated from their mothers during fishing operations [2,3]. This would not be recorded in mortality statistics, but could radically influence the recovery of the dolphin population. "Dolphins are very precocious animals," says Frank Fish of West Chester University, in West Chester PA. "We always marvel at wildebeest and other ungulates that start moving with the herd within 20 minutes of being born, but dolphins are moving constantly, so the neonate doesn't even have the luxury of 20 minutes."

Marine biologists studying dolphin behavior frequently see mothers and

calves swimming closely together at speeds of up to 2.4 m/sec, with young calves making little if any obvious swimming motions. The assumption is that the calf is **drafting** in its mother's **slipstream**, just as cyclists save energy by packing together during a race. The principle is widespread in biology. "We are always amazed at how smart animals are in their ability to conserve energy - such as ducklings' use of the flow pattern in the water that the mother produces as she swims along, so that they can reduce the amount of energy they need to expend to maintain that speed," says Fish. But in the case of dolphins there has never been any hard science aimed at seeing if this is a lovely myth or a physical reality.

Enter mathematician and aerodynamicist Daniel Weihs, who works at the Technion, Israel Institute of Technology, Haifa. He was involved in research some 25 years ago that aimed to find the speed dolphins needed to reach before they started jumping [4], and now he came back to the topic, looking for mathematical evidence of forces between mothers and calves (see the 'Behind the scenes' box for more of the rationale of the work).

Reduce complexity

The first task in making a mathematical model of a biological situation is to identify the dominant effects and simplify the issue. Once calculations are made in this simplified world it is relatively easy to add back the complications. Weihs started by assuming that dolphins are ellipsoidal in shape and that their bodies are six times as long as they are wide. Using a regular symmetrical object makes the equations much less complex, and previous studies had indicated that dolphin bodies were closely represented by an ellipsoid. On top of this, people working on torpedoes and other underwater weaponry had already developed equations that predict ellipsoid behavior in water.

Next, he assumed that the water is inviscid - that is, it has no viscosity.

This enabled him to employ d'Alembert's paradox. Named after eighteenth century French mathematician and physicist Jean le Rond d'Alembert, this paradox states that objects surrounded by an inviscid, incompressible liquid experience no drag as the liquid moves past. In doing this he had placed his theoretical dolphins into a simple Newtonian world where objects continue to move until influenced by some external force. "The main point here is that any single body under the conditions we are talking about produces no forces at all if it is moving at constant speed," explains Weihs. The question then is, what forces occur in this environment when you have two objects moving closely together?

Finally, he introduced two more assumptions: first, that the body shapes did not change during swimming; and second, that the dolphins were swimming at sufficient depth that they were not creating any surface waves. The results were clear. As the mother's body moves through the water, it pushes water sideways and outwards, and after she has moved forwards the water flows back in to fill the vacated space. "This means that if a second body is placed close enough to the first and within the area of forward motion of water, the relative velocity it feels will be less than its absolute velocity," notes Weihs.

Weihs' initial model showed that there were areas immediately in front of the mother dolphin, as well as to the side and behind, where a baby dolphin could swim and gain up to 90% of the force needed to move through the water from its mother. What's more, there were areas where Bernoulli attraction would actively pull a calf sideways, towards its mother.

Add in some reality

Life, however, is not that simple. Any baby dolphin that tried to stay immediately ahead of its mother would have great difficulty. "The situation," explains Weihs, "would be akin to

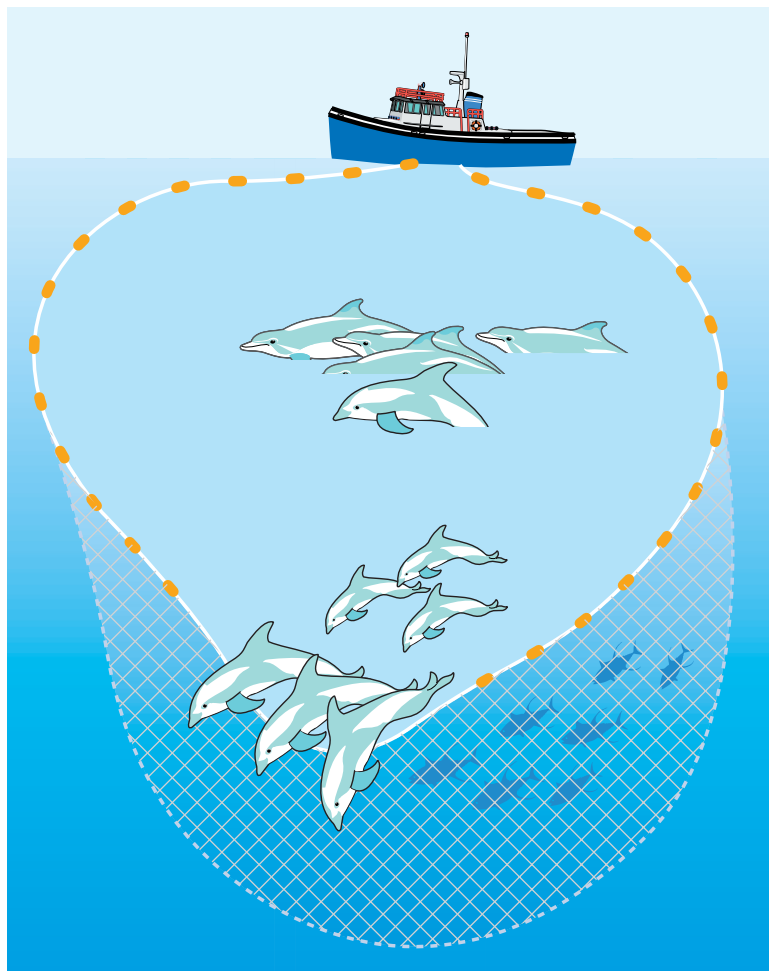


Figure 1

An illustration of how purse-seine fishing can allow some dolphins to escape while tuna are caught, as long as the dolphins can swim fast enough to escape the closing net.

pushing a string and expecting it to stay straight - it would be too unstable." Again, being immediately behind the mother wouldn't work, because a real dolphin moves by forcing a jet of water backwards, by flexing its body and using its tail flukes. While the initial calculations might suggest that immediately behind the mother was a great place, common sense shows that it wouldn't. At the same time, the flexing of the mother's body means that any zone directly above or below her would be too unstable to be helpful to a calf. This leaves the two zones on either side of the mother and about two thirds of

the way back as the two most stable and energetically favorable places for a youngster to hitch a lift.

Away from the mathematician's calculations, real dolphins also experience drag from the viscosity of the water. Adding this back makes the energy saving even more extreme. Any drag is proportional to the square of velocity, so positioning yourself in an area of forward-moving water allows you to experience much less drag. The energy required to achieve this velocity also increases as the cube of velocity. Consequently, any 10% saving in apparent velocity leads to a nearly 30% saving in

Behind the scenes

Journal of Biology asked Daniel Weihs about the motivation for his work on dolphin drafting.

What prompted this study?

I was contacted by Elizabeth Edwards of the US National Marine Fisheries Service to see if I could extend the earlier work I had done on dolphin hydrodynamics and start to look at the issue of drafting between mother and calf.

How long did the work take, and what is your reaction to the results?

Collecting data and background research took about three months, and the analysis another six. I was, as usual, amazed (but not surprised), both at the ways nature finds to apply physical principles to save energy, and in the strength of mathematical methods in identifying these.

How has the work been received, and where will you take it from here?

Many people have a similar reaction to my own, and an expectation of further steps to try and make use of this understanding to help reduce calf mortality. There are several obvious next steps. First, we must try to get further experimental verification by controlled experiments on live pairs and models. Second, we can add detail to the models, including a refining of the beneficial positions [of the calf relative to the mother], to include the fact that both forward and lateral forces act on the calf simultaneously. Third, and most important, will be to analyze fishing techniques to see if mother-calf separation during chases can be reduced by applying this new understanding to dolphin conservation.

energy. "The predicted force reduction is so substantial that it must play a major role in determining the calf's swimming position in practice," says Timothy Pedley, G. I. Taylor Professor of Fluid Mechanics in the Department of Applied Mathematics and Theoretical Physics at Cambridge, UK.

Dolphins do also rise to the surface and create surface waves. The energy used to create these waves constitutes another drag on the animals. Marine engineers calculate this as the Froude number, a non-dimensional coefficient defined as the ratio of inertial force to gravitational force. Applying this to the dolphins' situation reduces the effect of the previously mentioned gains. Consequently, swimming near

to the surface presents added problems to a calf that is trying to keep up with its mother. The point of interest for the tuna-fishing scenario is that in chase situations dolphins need to be nearer to the surface, as they need to breathe more frequently.

Having determined the hydrodynamic basis for drafting, Weihs then applied his calculations to photographs taken from helicopters of mother-calf dolphin pairs swimming together in the wild. His conclusion is that in this real-life situation the calves gain between 30% and 60% of the force required to keep up with their mothers [1]. "This is a very nice model and is almost certainly the explanation for the observations of drafting," comments

Pedley, adding: "it is not often that one can be so sure of the relevance of a mathematical calculation to biological phenomena."

Energetic advantage

"Weihs' paper establishes the basis for how drafting works between mothers and calves and indicates that drafting is really important to the mother-calf bond," says Edwards, from the National Marine Fisheries Service. What is now open to question is the extent to which drafting operates at the pace created in the tuna-fishing chase, when adult dolphins move by a combination of bursts of speed, leaps out of the water and brief periods of coasting. "Reviewing the literature shows that in a chase situation the mothers will probably just run away and 'assume' that the babies can just draft along side," Edwards comments.

Edwards would also like to refine the model to specifically address the limits to drafting, and compare these limits to the expected conditions during purse-seine tuna-fishing operations. This will help to determine whether fishery-related mother-calf separations are a likely source of unobserved dolphin mortality in the eastern tropical Pacific Ocean.

So, dolphin researchers believe Weihs' paper to be a good step forward, but as with all good research it generates a new layer of questions. "Weihs has given us the mechanical energetics of the situation. What we now need is an understanding of how this translates into metabolic demand," says Fish. "The model also needs to be developed to take in all the movements of the dolphin." Doing that will move the mathematics closer to the mammal, and may ultimately help to reverse the tuna-fishing-related decline in dolphin numbers.

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