

# The Nematocyst's Sting is Driven by the Tubule Moving Front

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## The phylum Cnidaria is equipped by nematocysts

The nematocysts are utilized by corals, sea anemones and jellyfish for prey capture, defense strategies and locomotion.

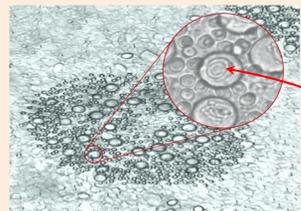
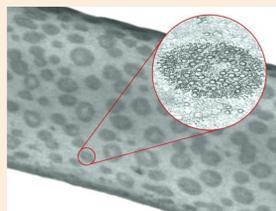
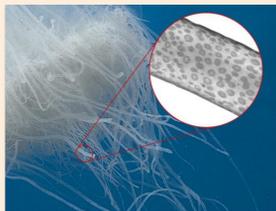


<https://www.letsurop.com/blog/explore-the-blue/unraveling-brain-coral/>

Photograph by David Doubilet  
<http://ngm.nationalgeographic.com/2010/01/download/doubilet-photography>

## Nematocysts are shown here along a *Rhopilema* tentacle

They are densely distributed along the tentacles and body surface, loaded and ready for firing. Once fired, they cannot be used again, but when still loaded, they can be effective even outside their biological cell.



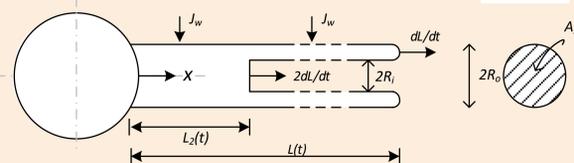
The tubule is folded inside the nematocyst capsule

## The elongation mechanism

Use this CR Code for an animation of the inside-out eversion



Upon activation, the tubule begins a fascinating inside-out eversion in which it elongates to reach a length of up to 100 times the capsule diameter. The matrix is made of large aggregates of poly- $\gamma$ -glutamate (p $\gamma$ Glu), initially trapped inside the capsule, but as water penetrates through the capsule wall, the resulting aqueous p $\gamma$ Glu solution leaves the capsule and fills up the tubule internal volume.



The common explanation suggests that an osmotic potential is building up inside the capsule owing to the matrix and the osmotic properties of the capsule wall, generating the required forces to fire and elongate the tubule. However, back-of-the-envelope calculation shows that water penetrating the capsule through its wall dilutes the p $\gamma$ Glu solution and the capsule loses most of its ability to continue pushing the tubule forward before its elongation is complete. Therefore, in addition to the capsule, another mechanism that can drive the tubule elongation must be identified.

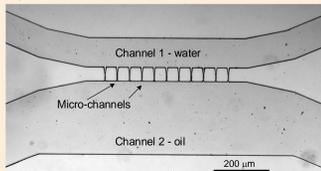
## The study hypothesis

The hypothesis is that the nematocyst tubule itself plays an important role in its own eversion

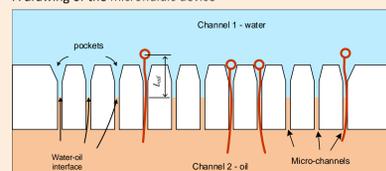
## The microfluidic platform

To test the hypothesis, we used a specially designed microfluidic platform to measure the elongation process while manipulating the osmotic potential along the tubule

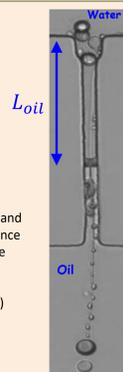
A picture of the microfluidic device



A drawing of the microfluidic device

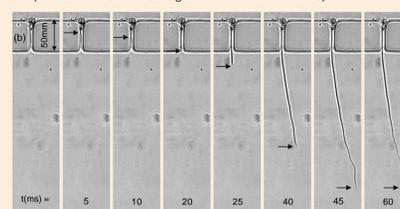


The narrow micro-channels connect between the water and oil channels.  $L_{oil}$  is the distance between the capsule and the water-oil interface. A few discharged nematocysts are sketched in red (not to scale)

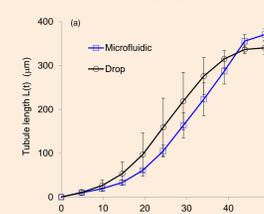


## Experimental results

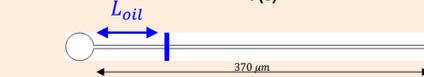
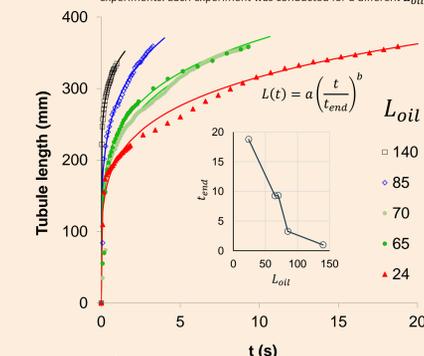
Snapshots of the tubule elongation in a water-water experiment



Comparison of the tubule elongation in the microfluidic device with results obtained in an unconstrained water drop

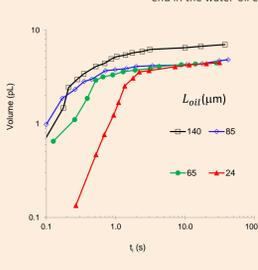


The tubule length as a function of time in the water-oil experiments. Each experiment was conducted for a different  $L_{oil}$ .



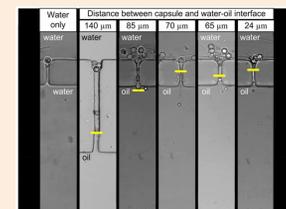
And yet another evidence...

The time evolution of the liquid volume, injected from the tubule far end in the water-oil experiments.



The tubule elongation movie.

It shows the elongation of the tubule in water-only and in the water-oil experiments. The activated capsule is marked by a dashed white circle and the location of the water-oil interface by a yellow line. The clock shows the elongation time in seconds and turns red when the tubule completes its elongation.



Use this CR Code to see the movie



Water that penetrate through the tubule wall will increase the total flow rate as  $Q = Q_0 + J_w 2\pi R_o L_{oil}$  and therefore the longer  $L_{oil}$  the higher  $Q$ .

The correlation between the liquid volume and  $L_{oil}$  serves as another evidence that the tubule wall is an osmotic membrane.

## The model results

To test the hypothesis, we used a specially designed microfluidic platform to measure the elongation process while manipulating the osmotic potential along the tubule. The experimental findings were analyzed by a mass transfer model developed here to represent the proposed elongation mechanism.

Use this CR Code for an animation of the p $\gamma$ Glu concentration



### Flow rate

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - 2\pi R_o J_w = 0$$

$$L_{oil} = 65 \mu m$$

$$J_w = 0$$

- $Q(x, t)$  - Flow rate
- $A$  - Cross sectional area
- $R_o$  - Outer radius
- $J_w$  - The water flux across the tubule wall

### Concentration of p $\gamma$ Glu

$$\frac{\partial C}{\partial t} + \frac{Q}{A} \frac{\partial C}{\partial x} + \frac{2\pi R_o J_w}{A} C = 0$$

$C(x, t)$  - p $\gamma$ Glu concentration

### Driving force, $F$

$$F = P_{drive} A_1$$

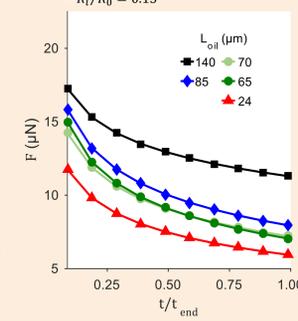
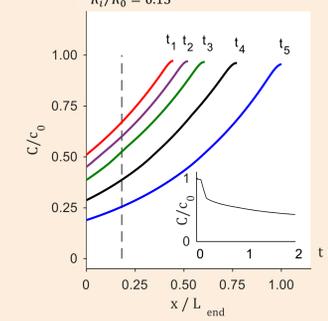
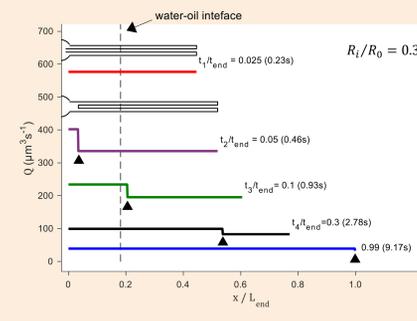
$P_{drive}$  is at the tubule end or at the water-oil interface

$$J_w = \alpha(\Delta\pi - \Delta P); \quad \pi(x, t) = iRTC(x, t)$$

The force is calculated for a given  $J_w/\alpha$

$$F = (RT C_{drive} - J_w/\alpha) A_1$$

where  $C_{drive}$  is either at the interface or at the tip



## Conclusions

While the paradigm was that the capsule acts as a pump that pushes the tubule forward, the results show that the osmotic potential in the tubule itself serves as a driving force like a locomotive that pulls the tubule behind it.



The inner folded tubule moves at twice the speed of the tubule front and, as a result, these forces are double what would have been needed if the tubule had not been everted inside out. This is analogous to pulley lift systems that apply only half the object weight, compensated by the double distance of the system chain. In order to generate such large forces, a high concentration and large osmotic potential must be developed at the tubule front.



These findings indicate that modifications of the immediate environment along the tubule route have the potential to slow down the process and assist in applications such as protection against jellyfish stinging. The new findings facilitate our understanding of potential prey defense strategies (such as the release of mucus or high osmotic solutions), but may also facilitate the development of osmotic based methods for nanotube production and drug delivery.