Science Advances

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Supplementary Materials for

Proton conductivity in ampullae of Lorenzini jelly

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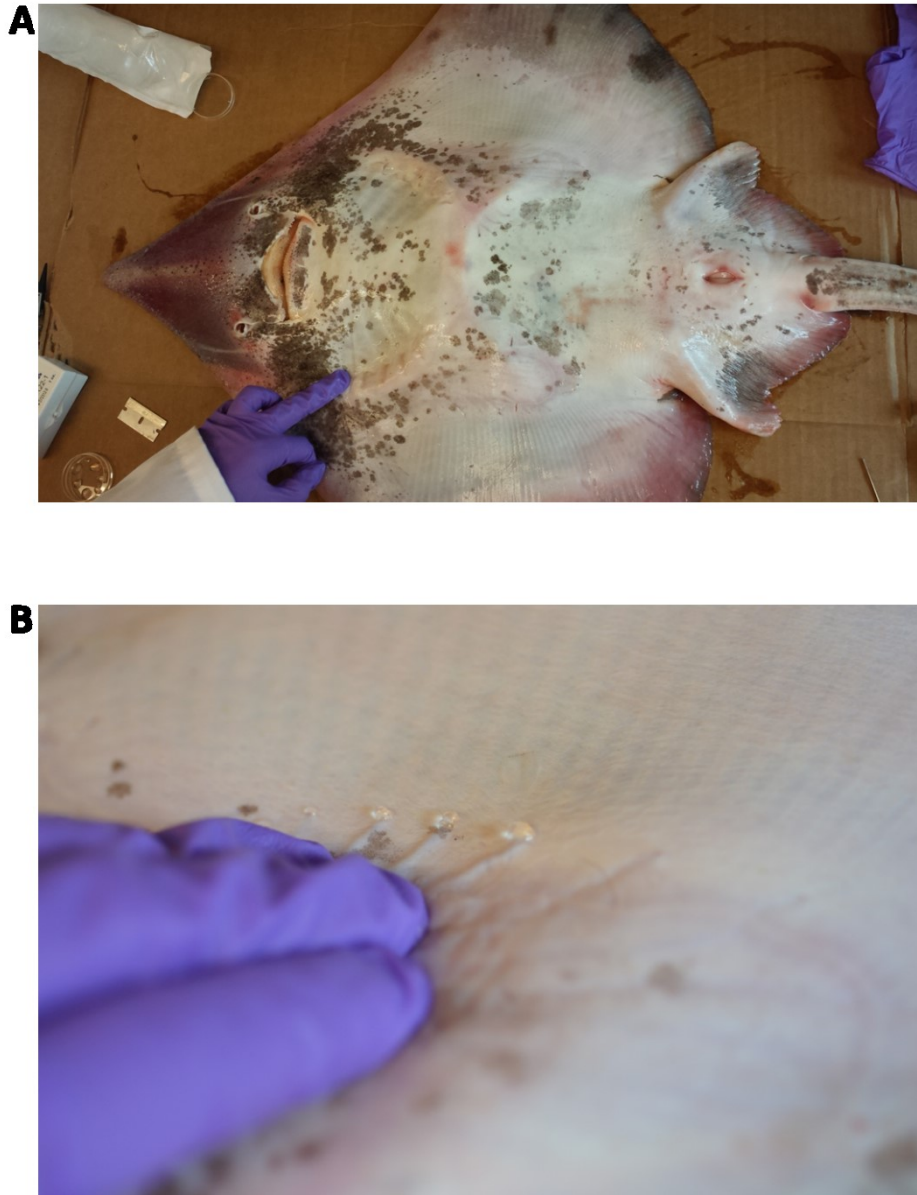
Supplementary Materials

fig. S1. Collection of AoL jelly. (**A**) The ventral side of an adult skate, *Raja binoculata.* Finger points to a region that contains many Ampullae of Lorenzini. (**B**) Pressing along the canals causes AoL jelly to extrude from the pores. [Photo Credit: E. E. Josberger, University of Washington]
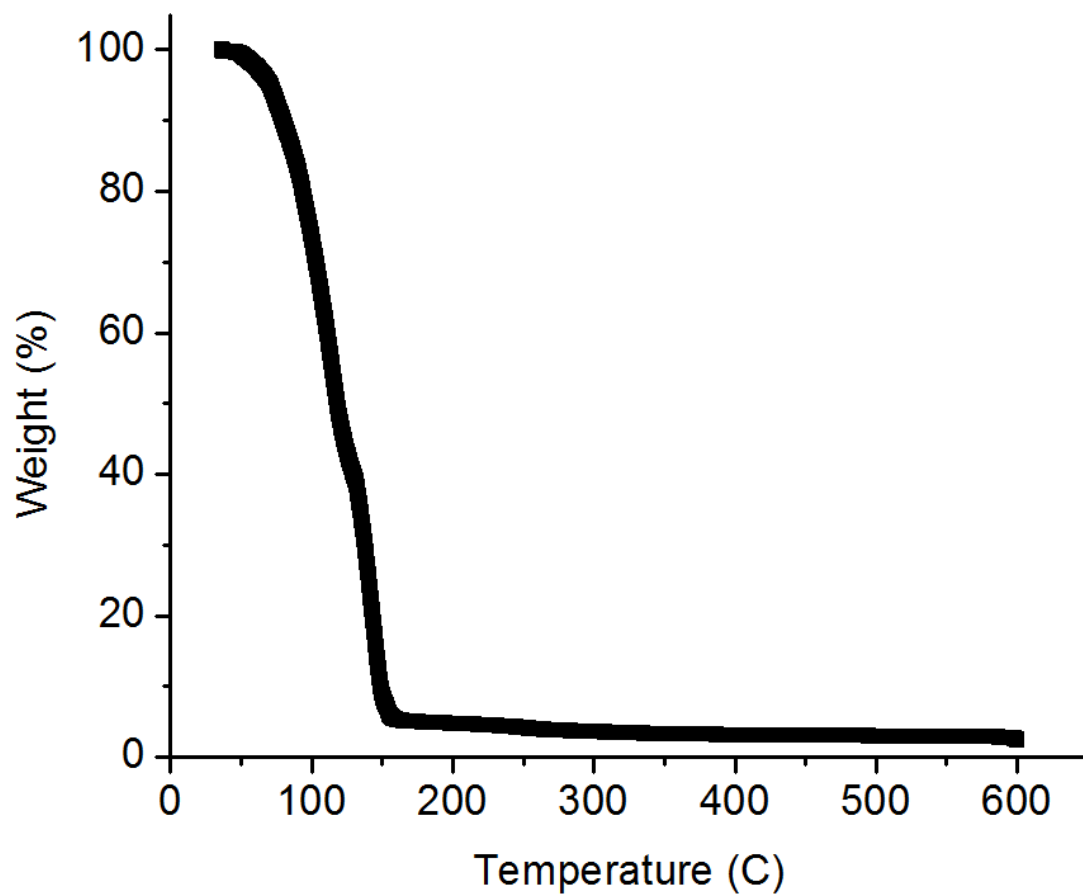
fig. S2. TGA of AoL jelly. 97% of the mass is lost between 47°C and 153°C, which corresponds to 97% water content of the AoL jelly.
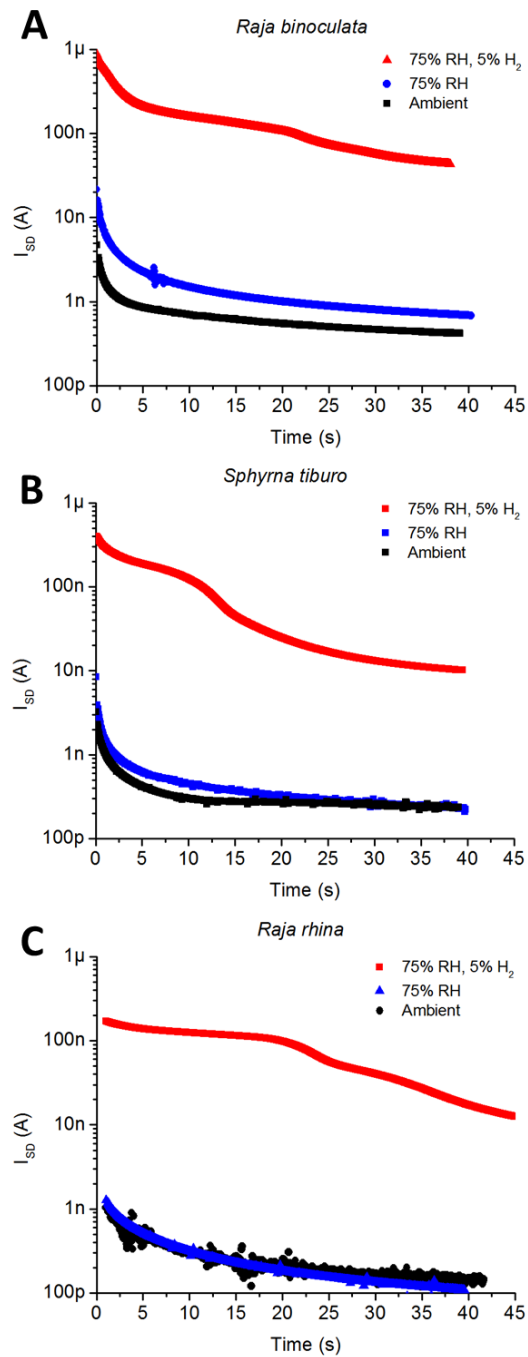
fig. S3. Cross-species consistency of results. Two-terminal DC measurements of ampullae jelly are similar to first approximation for the big skate (*Raja binoculata*, A), Bonnethead shark (*Sphyrna tiburo*, B) , and long-nosed skate (*Raja rhina*, C).
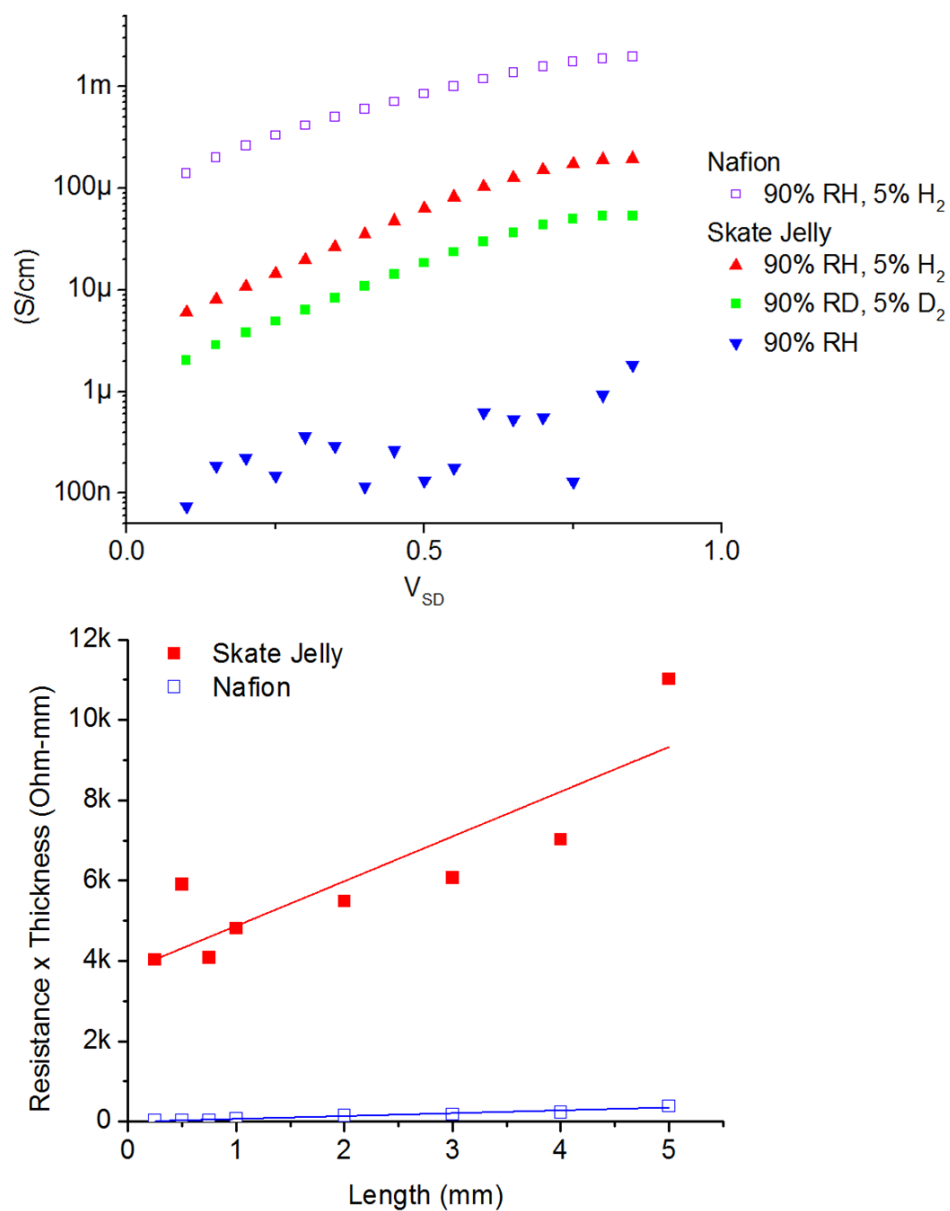
fig. S4. Control experiments on Nafion. (A) The conductivity of Nafion depends exponentially on the applied voltage. However, the magnitude of the conduction is much lower than the literature value of 78 mS/cm. This is likely due to fringing effects in the device geometry. **(B)** A TLM measurement of Nafion yields a conductivity of 28 mS/cm, compared with 2mS/cm for jelly. This is a slight decrease from the literature value of 78 mS/cm, which is attributed to sample preparation. The reported literature value is after immersion in heated sulfuric acid, while the measured sample was simply drop-cast from solution.

table S1. Elemental analysis of AoL jelly as analyzed by Intertek Pharmaceutical. The observed concentrations are similar to the average ion concentration in seawater (*11*).

Chemical Species	Observed Concentration
Cl	1.84%
Na	1.06%
SO_4^{-2}	0.22%
K	335 ppm
Br^-	<100 ppm
F^-	<100 ppm
Li	<100 ppm
NH_4	<100 ppm
NO_2^-	<100 ppm
NO_3^-	<100 ppm
PO_4^{-3}	<100 ppm

The brief transient current observed during a hydrated DC measurement (Fig. 1B, blue) is likely due to the motion of these ions and capacitative charging at the contacts. To verify this hypothesis, we calculated the protonic and ionic interface capacitances and compared to the observed capacitance in the I_{SD} vs t plot. The observed capacitance is found from $C = Q/V$, with Q the total charge and V the voltage. Integrating I_{SD} of the blue trace in Fig. 1B as a function of time, Q= 22nC at 1V. $C_{ISD}= Q/V= 22nF$.

The contacts are blocking Na^+ , Cl^- ions and H^+ and are transparent to electrons.

We the H^+ interface capacitance for the Debye layer as

$$C = \varepsilon A/\lambda_D \qquad \text{(eq. 1)}$$

A= contact area, ε= permittivity, and λ_D=Debye length

$$\lambda_D = (\varepsilon * k_B T/2 \ q^2 n)^{1/2} \qquad \text{(eq. 2)}$$

k_B=Boltzmann's constant, T=temperature, q = fundamental charge, and n = charge carrier density.

Estimating the proton mobility to be 5E-3 cm^2 / V s [the same as Maleic Chitosan (*12*)], we use σ = $qn\mu$ to find n = $2*10^{18}$ cm^{-3}. Estimating the permittivity to be $\varepsilon = 10\varepsilon_0$, we calculate $\lambda_D \approx 2nm$.

For a contact area of 30um by 500um, the total H^+ capacitance, C_{H+}= 0.6nF. Protons cannot be solely responsible for the observed charging using Pd contacts.

We calculate the ionic (Na^+ and Cl^-) interface capacitance using a similar procedure. Summing the Na^+ and Cl^- ions gives a total ion concentration of 3% (3 ions per 100 water molecules). We convert this to ions/cm^{-3} using:

$$n = (ions/water)*\rho/m \approx 10^{21} \text{ cm}^{-3} \qquad \text{(eq. 3)}$$

with ρ the density of water (1 g/cm^{-3}) and m the mass of a water molecule ($\approx 3*10^{-23}$ g).

Using eq. 1 and eq. 2, the ionic capacitance C_{NaCl}=13nF. Since there are two such interfaces in this device (source and drain), the total system capacitance is estimated to be 26nF. The observed charging capacitance at the contact (22nF) is consistent with Na^+ and Cl^-, not only H^+.

We note that the true material permittivity and mobility are unknown. In addition, this estimate ignores any possible bulk polarization capacitance in the material. Therefore, the results should be considered only a rough approximation to the true values.

table S2. Room-temperature proton conductivities of Nafion and known biopolymers.

Material	Conductivity (mS/cm)
Nafion(*21*)	78
AoL Jelly	**1.8 ± 0.9**
Maleic Chitosan(*12*)	0.7
Reflectin(*28*)	0.1
Bovine Serum Albumin (23)	0.05
Melanin(*16*)	0.02