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Electric eels: Bizarre natural phenomena or inspiration for novel nanocomposite energy storage

Erik Spoerke
Sandia National Laboratories, edspoer@sandia.gov

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Erik D. Spoerke, Sandia National Laboratories
PO Box 5800 MS 1411, Albuquerque, NM USA
T: 1 (505) 284-1932, edspoer@sandia.gov

Leo Small,[1] David Wheeler,[1] Alina Martinez,[1] Virginia Vandelinder,[1] George Bachand,[1,2] Walter Paxton,[1,2] and Susan Rempe[1]
1. Sandia National Laboratories, Albuquerque, NM USA
2. The Center for Integrated Nanotechnologies, Albuquerque, NM USA

The global rush to develop new high energy density, high power density electrical energy storage has motivated a variety of creative, alternative approaches to new technology development. We have adopted one such creative approach, looking to the electric eel as a model for how to manipulate and store electrical energy. These remarkable organisms are capable of repeatedly generating and discharging 1 Ampere of current at over 600V!

The cellular machinery responsible for electrical energy storage in organisms like the electric eel is quite complex (Figure 1), but the driving force behind these sophisticated processes hinges on the relatively simple concept of controlled transmembrane ion transport. In specialized cells known as electrocytes, coordinated ion channels and protein pumps shuttle ions across a membrane to create, maintain, or release ion concentration gradients. The chemical potential of these concentration gradients can be translated to a voltage, and the transport of ions across a membrane generates current. Although the amount of current and voltage established across a single membrane is quite small, by assembling thousands of electrocytes both in series and in parallel within its electric organs, the electric eel can accumulate the remarkable voltages and current necessary for its lethal electrical discharge.

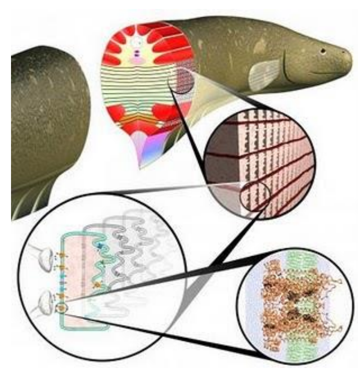

Figure 1. Schematic of the multiscale assembled biomolecular machinery involved in electrical energy management in an electric eel. (Adapted from Xu and Lavan, *Nat. Nanotechnol*. (2008) **3**, 666-670.)

In our work, we have established a simplified variation of Mother Nature's scheme, still focusing on the concept of controllably and selectively pumping and gating ions to generate, maintain, or release electrical potentials. In particular, our simplified scheme utilizes two cooperating nanocomposite membranes: a pumping membrane and a gating membrane.

The pumping membrane is a composite structure that relies on the light-activated proton pump bacteriorhodopsin (bR) as a one-directional ion (proton) pump, oriented within the membrane construct. When bR absorbs a photon, it responds by transporting one proton across a membrane, which means that an oriented array of bR is capable of using light to generate significant ion concentration gradients (and associated electrical potentials) across this "pump" membrane. In parallel, we are working to create a number of composite "gate" membrane structures that utilize, for example, electrochemically programmable chemistries applied to nanoporous substrates. These molecules, whose "gating state" is externally controllable with voltage, are expected to then maintain or release ion concentration gradients established by the bR pump membrane. We have discovered that by manipulating nanopore morphology, electrostatics, and solvation, these gate membranes can be used to rectify transmembrane ion transport, a critical capability needed to gate ions in this bio-inspired model system. Finally, we are working to address the concept of scalability, developing a system of microfluidic "cells" containing pump and gate membrane components in an artificial mimic of the series-parallel assembly of electrocytes in electric eels.

In the course of this presentation, I will describe this biomimetic scheme, explore the strategies, chemistries, and materials employed in the development of our programmable nanocomposite membranes, and discuss our efforts to mimic the type of ion-based electrical energy management so "shockingly" effective in an electric eel.

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