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Ionic cable

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ABSTRACT

This paper demonstrates a new type of interconnects to fulfill the primary function of axons: transmitting electrical signals over long distances and at high speeds. The interconnect, which we call "ionic cable", uses ions to transmit signals, and is built entirely with soft, elastic materials—elastomers and gels. The ionic cable is highly transparent, and remains functioning after being stretched nearly eight times its original length. We describe the design, theory and experiment of the ionic cable. We show that the diffusivity of signals in the ionic cable is about 16 orders of magnitude higher than the diffusivity of ions. We demonstrate that the ionic cable transmits signals up to 100 MHz over 10 cm, and transmits music signals over meters. The ionic cable transmits enough power to turn on light-emitting diodes. Our theory shows that the ionic cables scale well, suggesting tremendous opportunities to create miniaturized ionic circuit.

1. Introduction

In a robot and in an animal, the functions of sensing, deciding and acting usually locate in different places. Whereas the robot coordinates these functions using metallic wires, the animal does so using axons. The metallic wires are hard, but the axons are soft. This difference has inspired the development of stretchable electronics, devices that use patterned electronic conductors to achieve stretchability [1–4]. Recent work demonstrates examples of promising applications. Stretchable conductors replace dangling wires to connect a microprocessor to the fingers of a humanoid, or to the knees of an exoskeleton [5,6]. Wearable sensors are placed in contact with the skin of the user to collect healthcare data [7]. Electroceutical devices deliver electrical stimuli to neurons in rats and restore locomotion after paralyzing spinal cord injury [8]. A second difference between metallic wires and axons is also significant: metallic wires transmit signals using electrons, but axons transmit signals using ions. This difference has inspired the recent development of stretchable ionics, devices that use ionic conductors (such as hydrogels and ionogels) to achieve stretchability [9–12].

The stretchable ionic devices demonstrated so far have been actuators and sensors. Here we describe the design, theory and experiment of a family of ionic interconnect, which we call "ionic cable". The ionic cable mimics the

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function of an axon, not its anatomy. The axon transmits an action potential from head to toe at a speed over 100 m/s, while maintaining the amplitude of the action potential [13]. The action potential does so by continuously drawing energy through depolarizing the membrane of the axon. By contrast, the signal in our ionic cable will decay. We demonstrate, however, that the decay can be negligible. The ionic cable is analogous to a segment of an axon insulated by myelin sheath [13]. We show that the diffusivity of signals in the ionic cable is about 16 orders of magnitude higher than the diffusivity of ions. We demonstrate that the ionic cable transmits signals up to 100 MHz over 10 cm, and transmits music signals over meters. The ionic cable is highly transparent and stretchable; it remains functioning after being stretched nearly eight times its original length. Furthermore, the ionic cable transmits enough power to turn on light-emitting diodes. Our theory shows that the ionic cables scale well, suggesting opportunities to create miniaturized ionic circuits.

The stretchable ionic conductors integrate the two functions – stretchability and conductivity – at the molecular scale. A gel consists of a polymer network and a solvent (e.g., water or ionic liquids). The polymer network makes the gel a soft elastic solid, and the solvent makes the gel a fast ionic conductor. Gels can be as soft as tissues, and as tough as elastomers [14–16]. Although most hydrogels dry out in open air, hydrogels containing humectants retain water in environment of low humidity [17], and ionogels are non-volatile even in vacuum [10].

By contrast, stretchable electronic conductors are commonly hybrids of very dissimilar materials: elastomeric substrates to allow stretch, and electrical conductors to transmit signal. Commonly used electronic conductors include carbon in various forms (powders, fibers and sheets) [18–21], solid metals containing microcracks or patterned in serpentine shapes [22–24], and liquid metals [25]. These stretchable conductors have led to the demonstration of exciting applications, but their drawbacks have been noted: the stretchability is often limited [26], the repeated stretching and releasing may degrade the components that are not intrinsically stretchable [27], and liquid metals are hard to seal. Besides, these hybrids struggle to meet additional requirements in specific applications, such as biocompatibility in bio-mimetic sensors, and transparency in tunable optics [3,28,29]. On the other hand, many electronic conductors have high conductivity and can sustain direct current. These considerations suggest that stretchable ionic conductors and stretchable electronic conductors will find different applications that take advantage of their distinct attributes. The object of this paper is to demonstrate that ionic cables can transmit signals over long distances at high speeds.

2. Structure and scaling of ionic cable

The basic design of an ionic cable involves two parallel wires of ionic conductors, insulated from each other by a sheet of dielectric (Fig. 1). One end of the ionic cable serves as the input port, connecting through two electrodes to a signal of time-dependent voltage. The other end of the ionic cable serves as the output port, connecting through two electrodes to a load of impedance Z. The interface between an ionic conductor and an electrode forms an electrical double layer (EDL). For an ideal polarized electrode, so long as the applied voltage is within a range, e.g., between -1 V and $+1$ V, electrons and ions do not cross the interface, no electrochemical reaction occurs, and the EDL behaves like a capacitor [30]. To function without electrochemical reaction, the ionic cable is restricted to transmitting alternating current. Furthermore, the resistivity of ionic conductors is typically several orders of magnitude higher than electronic conductors.

We examine the consequences of these fundamental limits by developing a theory of ionic cable. We model the ionic cable as a special case of transmission line [31]. Let x be the coordinate along the cable, and t be time. The length of the cable is much larger than the spacing between the two wires. Each small segment of the cable behaves like a capacitor, which charges and discharges as the current flows in the wires. At a given time and a given segment of the cable, the charges on the two wires are of the same magnitude and the opposite signs. Let $+q(x, t)$ be the charge per unit length of one wire, $-q(x, t)$ be the charge per unit length of the other wire, and $v(x, t)$ be the voltage between the two wires. The magnitude of the charge relates to the voltage as $q = cv$, where c is the capacitance per unit length of the cable. The electric currents propagate along the two wires are of the same magnitude, but are in the opposite directions. Let $i(x, t)$ be the current along one of the wires. Ohm's law requires that $\partial v/\partial x = -ri$, where r is the sum of the resistances per unit length of the two wires. The conservation of electric charge requires that $\partial i/\partial x = -\partial q/\partial t$.

The theory shows that signal in the ionic cable runs fast, despite the high resistivity of ionic conductor. A combination of the above equations shows that the voltage $v(x, t)$ obeys the diffusion equation, $\partial v/\partial t = D\partial^2 v/\partial x^2$, with the diffusivity of signal being $D = 1/(rc) \approx (bd)/(\rho\varepsilon)$. Here b is the thickness and ρ the resistivity of the ionic conductor, whereas d is the thickness and ε the permittivity of the dielectric. Using the orders of magnitude representative of our experiments, $b = d = 1$ mm, $\rho = 10^{-2}$ Ωm and $\varepsilon = 10^{-11}$ F/m, we estimate the diffusivity of signal, $D = 10^7$ m^2/s. We note that the diffusivity of signal is many orders of magnitude higher than the diffusivity of ions in water, $D_{ion} = 10^{-9}$ m^2/s [32]. The enormous diffusivity of signal results from a feature in the design: the ionic cable consists of a conductor *and* a dielectric. Despite the high resistivity of ionic conductor, the permittivity of the dielectric is low, giving a small time scale, $\rho\varepsilon \sim 10^{-13}$ s. This time scale, together with the thicknesses of the conductor and dielectric, gives the large diffusivity of signal.

It is the high diffusivity of signal that enables the ionic cable to transmit a signal over long distance and at high frequency. A dimensional analysis of our theory shows that the signal decays negligibly if $l^2\omega/D \ll 1$, where ω is the frequency of the signal, and l is the length of the cable. For example, for $l = 1$ m, $\omega = 10^6$ Hz and $D = 10^7$ m^2/s, the dimensionless number is $l^2\omega/D = 0.1$. The ionic cable can, of course, transmit signals of lower frequencies over longer distances.

The theory also identifies another dimensionless number, $|Z|/rl$, the ratio of the impedance of the load to the resistance of the cable. When the impedance of the load is too small, the voltage drops across the load is small, and