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Biological Resources within the Human Body Can be Used to Operate Neural Implants

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Abstract—**Implantable neural devices have many therapeutic, diagnostic, and prosthetic applications. Although there have been exciting developments in constructing these devices, two critical problems, data communication between the implanted device and external computers as well as electrical power to the device, have not yet been solved. We investigate these problems using the volume conduction properties of the human body. A prototype implantable device is constructed equipped with a volume conduction data communication channel. A new power delivery antenna is conceptualized, inspired by a study of the power delivery mechanisms of electric fish. Our investigation indicates that the volume conduction resources within the human body may provide a powerful solution to both problems.**

Keywords—**Antenna Design, data communication, finite element simulation, neural engineering, neural implants, power delivery, telemetry, volume conduction**

I. Introduction

In spite of the rapid advances in the investigation of sophisticated neural implants, two crucial components in essentially all neural devices, an information link and an energy source, are not adequately studied. The existing designs often use a radio frequency (RF) transmitter or coupler for communication and a battery for power supply. These approaches suffer from the problems of inadequate operation distance and battery life when long-term and deep implantation within the brain is required. We adopt a different design concept in which the neural implant operates on the biological resources available within the human body. The volume conduction properties of biological tissue are employed to pass information and supply power. In order to support data communication, we have developed a new form of antenna, the "x-antenna" which directs electrical current to the location of reception and reduces the undesired current at the site of implant. A working prototype device with a volume conduction communication channel has been constructed in our laboratory.

Our investigation has revealed that the volume conduction channel can also be used to deliver a certain amount of electrical power from the scalp to an implanted device at a considerable depth. Energy delivery by volume conduction already exists in nature where certain fish (e.g., electric eel) use this mechanism to stun its prey. We study this energy delivery mechanism using finite element simulation. A new form of energy delivery antenna is conceptualized inspired by the biological structure and functionality of the electric fish. This antenna, which outperforms the traditional electrode pair antenna in our computer simulation, has an array of linearly distributed voltage sources.

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II. Volume Conduction in Biological System

In terms of electrical current conduction, the biological tissue can be modeled as a distributed, passive, and linear circuit[1]. The current-voltage relationship is given by the Poisson's Equation

$$\nabla \cdot (\sigma \nabla \phi) = \nabla \cdot \bar{J} \quad (1)$$

where ∇ is the gradient operator (a vector), ϕ denotes the potential (a scalar), J represents the impressed current density (or primary current density, a vector) which exists only within the region of the source[1], and σ is the conductivity which is assumed to be a scalar constant within a specified region of the volume conductor. Since we are only interested in ϕ outside the small region where the primary current J is present, the right side of (1) is zero within the region of interest. With these simplifications, Eq. (1) becomes Laplace's equation:

$$\sigma \nabla^2 \phi = 0. \quad (2)$$

Eq. (2) is solved by using the finite element method (FEM) which requires a discretization of the problem domain into a set of small building blocks called elements. This discretization processing is called meshing. The partial differential equations describing the physical problem are approximated by a set of algebraic equations on the mesh. These algebraic equations are solved numerically to approximate the original continuous solution over the interested domain. In order to obtain a solution specific to the simulation problem, a set of boundary conditions must be specified between the volume conductor layers with different conductivity values and on the outside surface of the volume conductor. The Dirichlet boundary condition specifies a potential on a closed boundary surface, while the Neumann condition specifies the derivatives at the normal direction of the surface[2]. For example, the Neumann condition in the form of gradient of a function is set at the conductor surface to reflect the fact that no current can escape from the physical domain of the volume conductor.

III. Volume Conduction for Communication

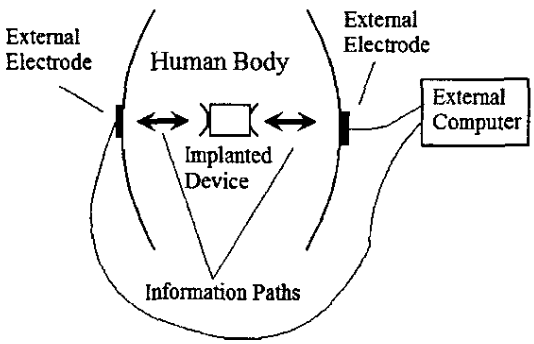

Fig. 1: The implanted device (center) contains two antenna elements illustrated as two curved shapes attached to the body of the implant shown as a rectangle. A pair of external electrodes receives/transmits signals (double arrows) from/to the antenna elements through biological tissue.

The main components of the communication system are illustrated in Fig. 1. The implantable device inside the human body contains sensors, actuators, and electronic circuits. The outside of the device has a pair of antenna elements facing another pair of external electrodes on the body surface (e.g., scalp). Information is transmitted in the form of an electric field distribution. The skin-surface electrodes are connected to a wearable computer which processes information. Because electromagnetic waves are not required in the volume conduction based communication system, the frequencies of transmitted signals can be in the kilo-Hertz range. The information system built upon volume conduction avoids the strong shielding effect of ionic fluid in the body, requires simpler electronic circuit than the RF circuit, and consumes a smaller amount of power to operate[3], [4], [5], [6].

A. Implantable Volume Conduction Antenna for Communication

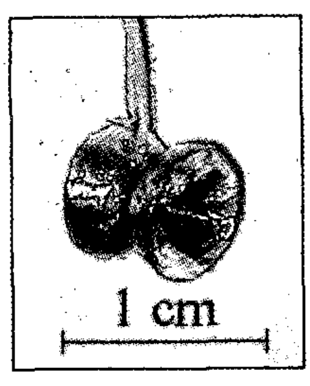

Fig. 2. A test version of x-antenna

We have previously studied the x-antenna and have shown that it significantly out-performs other forms of antennas in terms of transmission efficiency, power consumption, and reduction of undesired neural stimulation at the implant site[3], [4], [5]. The x-antenna has two elements designed in concave shapes resembling the letter x. A test version of the x-antenna is shown in Fig. 2.

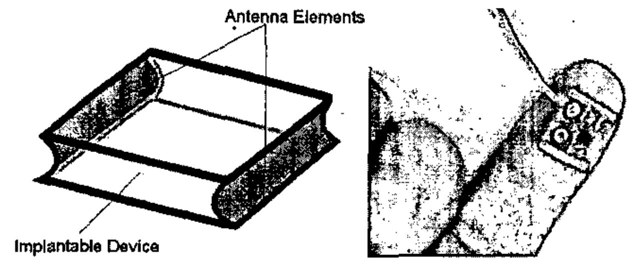

Fig. 3. Left: The two x-antenna elements serve as the side panels of the implant; Right: A partially constructed experimental neural implant at which the wires are connected to the recording electrodes on the cortex.

A more application-oriented x-antenna design is shown in the left panel of Fig. 3. The two antenna elements are located on the side panels of a prototype implantable device for experimental evaluation on laboratory animals. This design has several desirable features: 1) it utilizes the body of the implantable device as the previously described insulator to reduce shorting current, 2) it provides a large separation of the two antenna surfaces, 3) it takes little internal or external space of the implantable device, and 4) it does not require a supporting mechanism to stabilize the antenna. The electronic circuitry, which was encapsulated by clear epoxy, was constructed on a double-sided printed circuit board (only one side of the circuit can be observed in the right panel of Fig. 3. The dimensions of the implantable device were approximately $10 \times 12 \times 3$ mm^3. Although this size was relatively large for some neural implants, it can be reduced significantly in the future with large-scale integrated circuits.

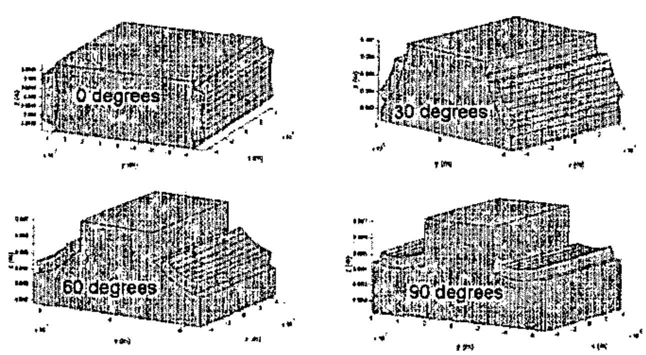

Fig. 4. Variation in Antenna Orientation

B. Computer Simulation

Computer simulation using the finite element method is an effective tool for design, evaluation, and optimization of the volume conduction antenna. We have been developing finite-element models which allow us to compute and visualize both the current density and potential fields generated by the x-antenna within a volume conductor. One important parameter for the antenna is the orientation of each antenna element. We define the orientation to be the rotation angle of an antenna element with respect to the middle plane of the device body (see Fig. 4). The optimal value of the orientation is determined by computer simulation.

The left panel in Fig. 5 shows a two-dimensional simulation of a central cross section of an implantable device with a pair of x-antennas. In this design, we utilized a reflector (the extended portion in the bottom of the device) which drives the current flux toward the scalp to maximize the signal strength in the far field.

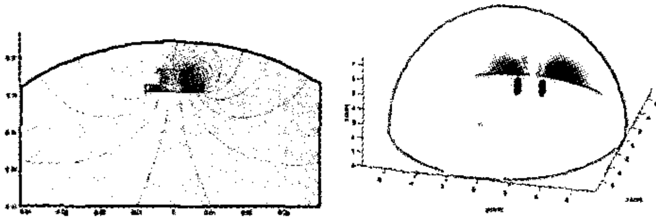

Fig. 5. Simulated potential field generated by x-antenna. Left: 2-D simulation, RIGHT: 3-D simulation

The right panel in Fig. 5 shows an example of the head (modeled as a sphere) implanted with a x-antenna. In this computational model, each surface in the "x"-shaped elements is a portion of an ellipsoidal surface. Note that the two antenna surfaces in this case are placed at an angle roughly facing the two high-intensity regions on the surface of the sphere where the reception electrodes should be placed to achieve the highest signal-to-noise ratio. For clarity, only the upper half of the spherical model is displayed. Detailed descriptions about our simulation methods and antenna parameter optimization have been provided elsewhere[7].

Our computer simulation enables us to compare shape, dimension, depth, angle, and other important parameters of the volume conduction antenna quickly and analytically to optimize antenna design. Without using this powerful computational tool, these parameters may have to be measured using an experimental trial-and-error approach, which is time-consuming and expensive.

IV. Bio-Inspired Energy Delivery Antenna

In principle, volume conduction is capable of not only passing information, but also delivering power. Although a volume conduction based power delivery system for implantable devices has not been built, this mechanism already exists in nature where the electric eel, electric stingray, and other aquatic creatures deliver energy[8]. For example, the South American electric eel, a strongly electric fish, is capable of discharging 500V (head positive) at a maximum pulse frequency of 25Hz into its surrounding water through synchronized discharging of voltage generating cells known as electrocytes in the body[9]. Weakly electric fish typically generates less than one volt in amplitude. Although the electric field of this type of fish cannot be used to stun prey, it can be used for navigation, object detection, and communication[8].

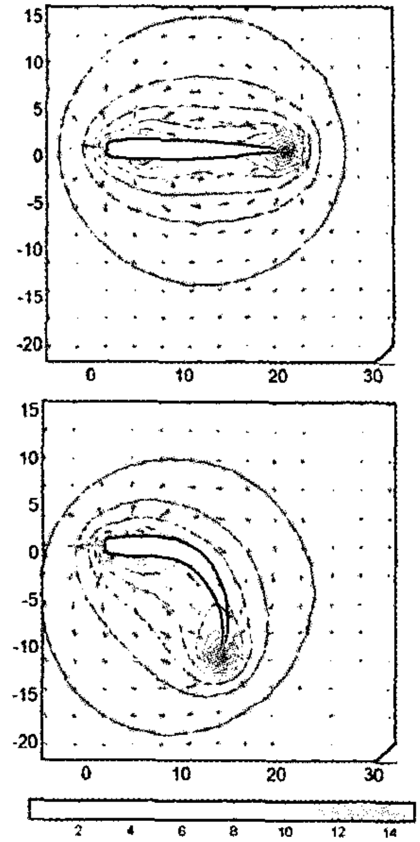

Fig. 6. Simulated electric field (e.g., gradient of potential, shown as arrows) distribution of South American electric eel without (top) and with (bottom) tail bending. The black curves and color represent the strength of the electric field.

It is interesting to observe that the weaponry organs of the strongly electric fish are arranged in a linear form. Each column of 5,000 to 10,000 electrocytes, connected in series, spans approximately 80% of the electric eel's body. Approximately 70 columns are arranged in parallel on each side[10]. To simulate the discharge of the electric eel using finite element analysis, we approximated the electric eel in a top-down cross section and placed it in a cross-section of a large "fish tank". Our 2-D simulation results are shown in Fig. 6 where black curves and color both represent equal electric field strength, and arrows denote current density vectors whose length is proportional to the electric field strength. It can be observed that tail bending distorts the surrounding electric fields. Larger (smaller) fields are induced in the concave (convex) side. This indicates that the shape of the body helps to redistribute and focus electric energy.

The electrophysics of the electric fish inspired us to study the energy delivery problem using volume conduction. Fig. 7 shows the potential gradient and current density within a conductive circle modeling a cross section of the human head. The result of a "linear source distribution antenna", which has a similar structure to the weaponry organs of electric eel, is

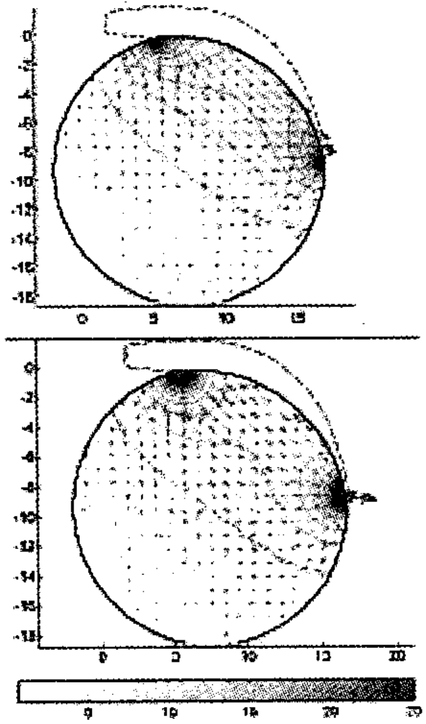

Fig. 7. Electric field (V/cm) and current density vectors of the bio-inspired linear source antenna (top) and the traditional electrode pair antenna (bottom).

shown in the top panel and that of the traditional electrode pair antenna is shown in the bottom panel. Comparing the flow lines of the arrows in the upper right section in both panels, it is clear that a higher power density is induced by the fish-like linear source antenna within a target region of the brain.

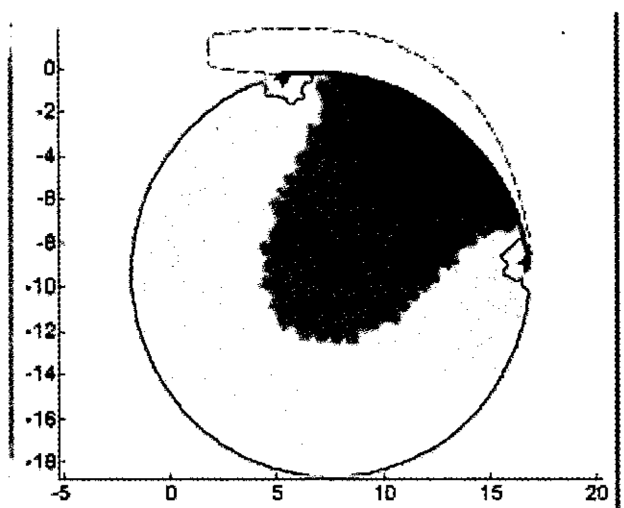

Fig. 8: Comparison between linear source antenna and electrode pair antenna with an equal current emission. The black shaded region immediately below the right part of the antenna receives significantly more energy in the case of the linear source antenna.

We measured the current distributions induced by the linear source antenna, c_1, and the electrode pair antenna, c_2, and calculated their relative percentage, r, $r = (c_1 - c_2)/c_2 \times 100\%$, at each location within the simulated domain. Fig. 8 shows the results where the black shade, dark shade, light shade, and white shade, respectively, represent $r \geq 25\%$, $0 \leq r < 25\%$, $-25\% \leq r < 0\%$, and $r < -25\%$. It can be observed that the linear source antenna delivers significantly more energy to a region immediately below the active portion of the antenna. It can also be observed, since the new antenna emits currents spanning a region rather that two current emitting poles, the problematic effects of local heating and undesired stimulation to excitable tissues are significantly reduced.

V. Conclusion

We have investigated the use of biological resources existing within the human body, the volume conduction properties of biological tissue, to construct data communication and energy delivery channels for implantable devices. Our approach has several advantages over the existing radio frequency approach in that our approach is more energy efficient, requires simpler circuits, and avoids the shielding effect of the ionic fluids within the human body. A prototype device has been constructed capable of communication using volume conduction. An energy delivery antenna with linearly distributed sources have been conceptualized, inspired from the study of the energy delivery mechanism of electric fish. Our simulation has shown that the new antenna produces stronger, focused, and deeper power penetration than the traditional dipolar antenna.

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