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Analysis of Fractal Electrodes for Efficient Neural Stimulation

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Abstract— **Planar electrodes are increasingly used in a variety of neural stimulation techniques such as epidural spinal cord stimulation, epidural cortical stimulation, transcranial direct current stimulation and functional electric stimulation. Recently, optimized electrode geometries have been shown to increase the efficiency of neural stimulation by maximizing the variation of current density on the electrode surface. In the present work, a new family of modified fractal electrode geometries is developed to increase the neural activation function and enhance the efficiency of neural stimulation. It is hypothesized that the key factor in increasing the activation function in the tissue adjacent to the electrode is to increase the "edginess" of the electrode surface, a concept that is explained and quantified by fractal mathematics. Rigorous finite element simulations were performed to compute the distribution of electric potential produced by proposed geometries, demonstrating that the neural activation function was significantly enhanced in the tissue. The activation of 800 model axons positioned around the electrodes was also quantified, showing that modified fractal geometries yielded a 22% reduction in input power consumption while maintaining the same level of neural activation. The results demonstrate the feasibility of increasing stimulation efficiency using modified fractal geometries beyond the levels already reported in the literature.**

I. INTRODUCTION

Electrical stimulation of the nervous system is a technique used to restore function to individuals with neurological impairment. Implanted planar electrodes have been used extensively in the past few years for efficient stimulation of both central and peripheral nervous systems, in many applications. Epidural spinal cord stimulation (ESCS), for example, uses electrical stimulation of the dorsal roots and/or the dorsal columns of the spinal cord to address various pain syndromes [1]. Recently, the combination of ESCS and partial weight bearing therapy has been shown to induce functional gains in over-ground gait for individuals with chronic, incomplete spinal cord injury who have very low motor scores in their lower limbs [2]. Within the brain, epidural cortical stimulation (ECS) provides useful intervention for neuropathic pain [3], movement disorders [4], Parkinson's disease [5], and stroke rehabilitation [6]. Deep brain stimulation (DBS), which involves high frequency electrical stimulation of the thalamic or basal ganglia structures to treat movement disorders, has rapidly emerged as an alternative to surgical lesions [7].

In such applications, electrodes are powered by implanted pulse generators (IPGs) which use primary cell batteries and require surgical replacement when the battery is depleted. Surgical replacement is expensive and carries substantial risk. For example, the complication rate is three times higher for replacement of cardiac pacemakers than for original device placement [8], and the complication rate for replacement of implanted defibrillators is 8.1% [9].

Although much effort has been put into finding optimal anatomical targets for different nerve stimulation techniques, very little work has been done to improve the efficiency of nerve stimulation by using intelligent designs and configurations of electrodes themselves. In particular, electrode geometry can affect the spatial distribution of the electric field in tissue, and thus the pattern of neural excitation. The electrode design also impacts the effective impedance, and thus the power consumption. Reduced power requirements can extend the lifetime of existing IPGs, thus reducing both cost and risk associated with repeated IPG replacement surgeries. Alternatively, reduced power requirements also could enable the use of smaller batteries, allowing IPGs to be reduced in size.

In the present work, a new family of fractal electrodes is introduced for efficient neural stimulation. Electromagnetic modeling results indicate that the proposed geometries produce a significantly higher neural activation function, providing as much as a 22 % reduction in power consumption while maintaining the same percentage of neural activations achieved by conventional electrodes. The proposed electrode designs can be implemented with existing manufacturing techniques and will not require the exhaustive biocompatibility testing that is necessary for new materials. However, there is no barrier in principle to combining the fractal electrode approach with new materials, to maximize the efficiency of stimulation even further.

II. MATERIALS AND METHODS

A. Overview

One approach to increase the efficiency of neural excitation by altering the electrode geometry is to maximize the neural activation function (AF), which is proportional to the second spatial derivative of the extracellular potential, V_e [10]. The activation function AF can be written in terms of the electric field E and electric current J as:

$$\mathrm{AF} \propto \frac{\partial^2 V_e}{\partial z^2} = -\frac{\partial(E_z)}{\partial z} = -\frac{1}{\sigma}\frac{\partial(J_z)}{\partial z} \quad (1)$$

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where z is the direction along the axon and σ is the conductivity of the medium. Because AF is proportional to the spatial derivative of the electric field, it can be maximized by increasing the irregularity of current profile on the surface of the electrode. Recently, planar geometries have been proposed to maximize activation function by increasing the perimeter of the electrode [11]. An interesting alternative hypothesis is that the increasing electrode perimeter is not the key modification of interest, but rather increasing the irregularity of the surface current profile. The irregularity can be quantified by defining a metric known as topological "edginess". This concept naturally leads to the development of fractal shapes as candidate electrode geometries, which increase topological edginess while maintaining the amount of total current delivered to the tissue. This new, alternative hypothesis is validated by performing a rigorous finite element analysis of field distributions to estimate the neural activation function.

B. Background

In essence, a fractal is a fragmented geometric shape that can be split into parts, with each part appearing (at least approximately) as a reduced-size copy of the whole - a property called self-similarity. The original inspiration for developing fractal geometries came largely from in-depth scrutiny of galaxies, cloud boundaries, snowflakes, trees, leaves, and other self-similar patterns found in nature. Applications of fractals are now widespread in many branches of science and engineering [12]. For example, in fractal electrodynamics, fractal geometry has been combined with electromagnetic theory specifically to propose improved designs to control the radiation pattern, wave propagation, and scattering characteristics of radio-frequency devices [13, 14] and a number of patents have been filed using fractal shapes to improve design of antennas or frequency selective surfaces [15-17].

At present, however, use of fractal geometries to control the static electric field distribution in tissue, desirable for improving neural stimulation, is a novel concept that remains to be explored.

C. Modified Sierpinski-Based Electrodes

Figure **1** shows the first few stages on constructing the Sierpinski carpet [18], a well-explored fractal shape widely used in designing radiating elements in phased array antenna systems. The procedure starts with a base square (first stage). Next, the square is divided into 9 congruent sub-squares in a 3×3 grid, and the central sub-square is removed (second stage). The same procedure is then applied recursively to the remaining 8 sub-squares (third stage), and then can be repeated an infinite number of times.

One metric used to quantify the complexity of fractal shapes is called the fractal dimension [19], given by the ratio of the change in detail to the change in scale. For sets describing ordinary geometric shapes, the fractal dimension equals the Euclidean or topological dimension: 0 for sets describing points; 1 for sets describing lines; 2 for sets describing surfaces; and 3 for sets describing three dimensional geometries. However, unlike topological dimensions, the fractal index can take non-integer values, indicating that a fractal set fills space in a quantitatively different fashion than an ordinary geometrical set [20].

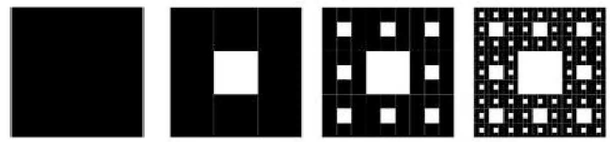

Figure 1: Stages in constructing Sierpinski carpet fractals

In Figure 1, let N_n be the number of black boxes, L_n the length of a side of a white box, and A_n the fractional area of black boxes after the nth stage of construction. Assuming that the base square has a unit area equal to 1, then for n≥0:

$$N_n = 8^3 \quad (2a)$$

$$L_n = 3^{-n} \quad (2b)$$

$$A_n = L_n^2 N_n = \left(\frac{8}{9}\right)^n \quad (2c)$$

The capacity dimension d is defined as [21]:

$$\mathrm{d} = -\lim_{n\to\infty} \frac{\ln N_n}{\ln L_n} = 1.892789 \ldots \quad (3)$$

Notably, the capacity dimension of this fractal is less than 2, the value for a solid surface. In other words, the "edginess" of the geometry has been increased which, when fabricated as an electrode, is hypothesized to lead to a substantially increased activation function.

In progression toward higher fractal stages, the total metallic surface of the electrode will inevitably be reduced. This could have negative impact on the efficiency of neural excitation, as the total amount of current delivered to the tissue could be reduced. In anticipation of this problem, modified electrode geometries were developed that included systematic re-attachment of cut-out parts to ensure constant total metallic surface area, while maintaining increased surface irregularity. Figure 2 shows the process of building a second order modified Sierpinki's fractal surface.

D. Finite Element Modeling

Full-wave methods have been extensively used to address the interaction of electromagnetic waves and living tissues [22-25]. In this work we have used finite element method (FEM) to investigate the performance of proposed modified fractal electrodes. Three-dimensional (3D) models of fractal electrodes were developed inside a 3D homogenous conducting medium (see Figure 3). The model included the electrode surface with a potential of -1 V and a homogenous volume conductor representing the neural tissue (σ = 0.2 S/m [26]). The tissue adjacent to the electrode was modelled as a cylinder with a diameter of 10 cm and a height of 10 cm and the outer boundaries set to V = 0 to simulate the cathodic monopolar stimulation. The 3D models were implemented in Ansys Maxwell 3D and were partitioned into ≥1800000 tetrahedral elements. To ensure the high accuracy of FEM results needed for further simulation of neural activation, a high resolution cylindrical region was introduced around the electrode (diameter of 40mm and height of 40mm) as depicted in Figure 3 where the mesh size was <0.5mm. The FEM solver was set to follow an adaptive iterative process whereby an initial mesh was seeded according to the geometrical details of the structure. The Maxwell3D electrostatic solver computed and stored the value of the electric potentials at the vertices and midpoints of the edges of each tetrahedron in the finite element mesh. The scalar potential field V was calculated under the quasi-static assumption by solving Laplace equation $\nabla \cdot (\sigma \nabla V) = 0$ as well as the electric field according to $E = -\nabla V$. After E was calculated, Maxwell3D provided solution files and an error analysis. In adaptive analysis, the solver refined the tetrahedra with the highest error, and continued solving until the stopping criterion was met. The adaptive solver refined the mesh by 30% at each iteration and iterated until the difference between two successive solutions was < 0.5%.

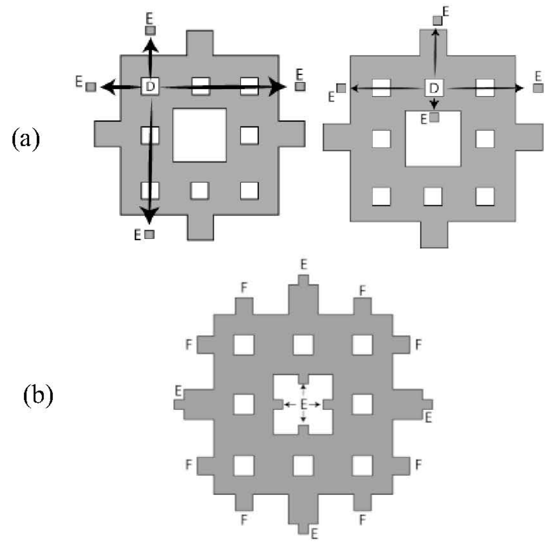

Figure 2: Building a second order modified Sierpinski square. (a) Squares of area D at the corners of a rectilinear interior pattern are cut out and divided into four smaller squares of area E=D/4 to be attached to outer boundary of electrode as shown by arrows. (b) Squares placed at the same location are merged into a single larger square of equivalent surface area F=3×E.

III. Neural Activation Prediction

The NEURON environment tool [27] was used to model a population of 800 axons distributed in a cubic area of 4cm×4cm×2cm above the electrode. Neurons were modelled as 57μm-diameter myelinated axons made of 21 nodes of Ranvier separated by 20 internodes as in other modeling studies of neural stimulation in the literature [28, 29]. The potential distribution V_o was extracted from the FEM model from a high-resolution cubic area located 15mm above the surface of the electrode (Figure 3) and applied as the extracellular potential to the electrical model of the axons. A 15 mm gap was introduced to account for the presence of the peri-electrode space - a region filled with extracellular fluid that is formed in the acute phase after electrode implantation [30].

A square electrode, first order modified Sierpinski carpet, and second order modified Sierpinski carpet electrodes were modeled and simulated. The percentage of axons activated was computed for each simulation scenario. A time varying field potential was created by convoluting the obtained potentials by a normalized time varying electric pulse of 60μs width, as is typically used in stimulation techniques such as DBS.

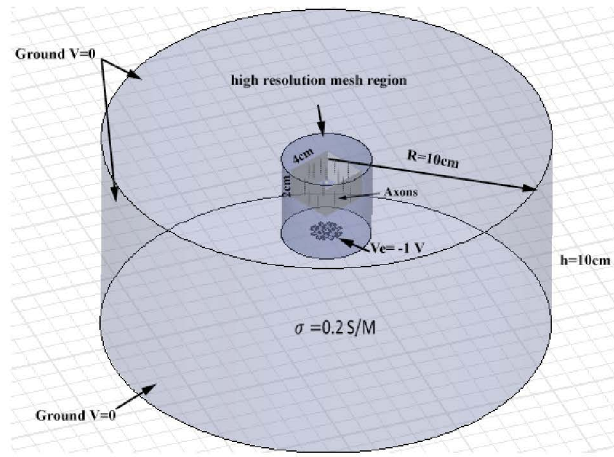

Figure 3: Geometry of the finite element model of a planar electrode adjacent to a cylindrical homogenous volume conductor.

IV. Numerical Results

Based on the modeled population of axons, as described above (also see Figure 3) input–output curves were generated of the percentage of activated axons as a function of stimulus amplitude (Figure 4) and stimulus power (Figure 5). Modified fractal electrode #2 decreased the average threshold voltage by 10% and decreased the average power consumption by 22%, as compared to the conventional square electrode. The first order modified fractal electrode (#1) produced intermediate levels of improvement.

V. Discussion and Conclusion

In this contribution, fractal-shaped electrodes were developed and applied to manipulate the distribution of the electric field inside tissue, substantially improving neural stimulation. Implanted planar electrodes, as a crucial component of neurostimulator devices, have vast applications in neural stimulation of the human central and peripheral nervous system. Applications are rapidly growing, from treating pain syndromes to facilitate stroke rehabilitation and treating a variety of neurological disorders. In the majority of neurostimulator devices, the electrodes are empowered by implanted pulse generators (IPGs) and require surgical replacement when the battery is depleted. Considering the substantial complication rate and costs of a replacement surgery, it is highly desirable to prolong the life time of implanted batteries by reducing the required input power while maintaining a high level of neural activation. This could also enable using smaller IPGs, which are more convenient for both patients to tolerate and for surgeons to implant efficiently.

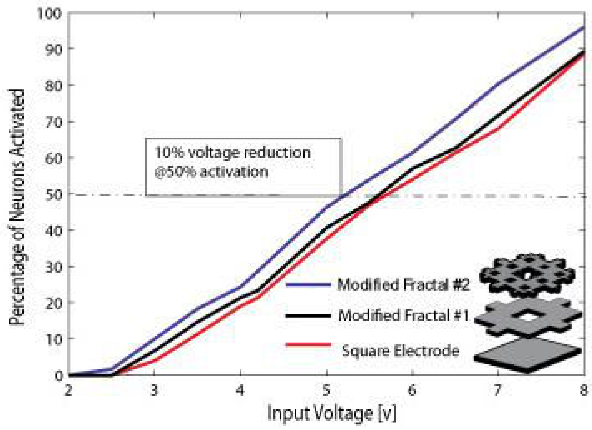

Figure 4: Input–output curves of activation of model axons: Percent of activated axons as a function of stimulus voltage

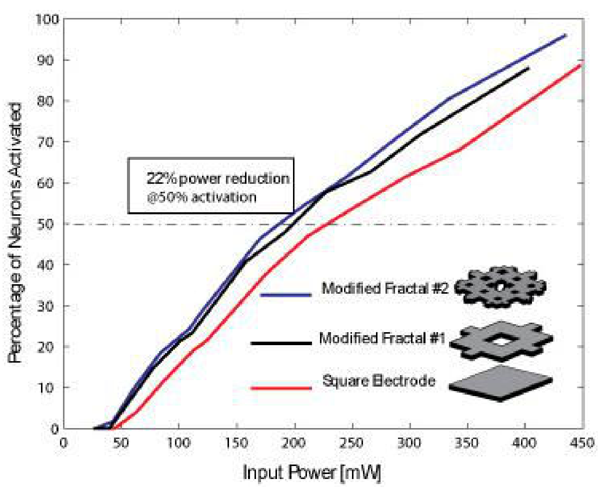

Figure 5: Input–output curves of activation of model axons**:** Percent of activated axons as a function of input power

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