

# SIMULATION OF PARALLEL CURRENT INJECTION FOR USE IN A VISION PROSTHESIS

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**Abstract**—A 2D computational model was developed and used to simulate the distribution of voltage arising from multiple parallel current sources connected to an electrode array and immersed in a bath of physiological saline. The model was solved using a custom spectral collocation method. Pairs of electrodes placed in various locations within the bath were simulated in order to quantify return current interaction between parallel sources. A more complex electrode array geometry based on an anticipated hexagonal electrode array - to be used in a vision prosthesis - was also investigated. The guarding affect of the hexagonal array, as opposed to more traditional bipolar electrode arrangements was clearly demonstrated.

*Keywords* – vision prosthesis, modeling, current source, retina, neurostimulation

## I. INTRODUCTION

Current commercial devices used for electrical stimulation of neural pathways or muscle require either single (e.g. cardiac pacemaker) or relatively few (e.g. cochlea) electrodes that are interfaced with neurostimulation electronics. In many cases, the implanted electronics multiplexes a single current source across specific target electrodes. Thus a serial mode of stimulation is utilized.

With the possible exception of functional electrical stimulation (FES) and vision prosthetics, no end organ has required stimulation rates that would necessitate stimulus strategies and data throughput rates that would require a deviation from a serial mode of stimulation. Initial research [1, 2] in the area of epi-retinal vision prosthetics has adopted the traditional serial approach.

More recently, our group [3, 4] and others [5] have been investigating alternate simulation paradigms that could be incorporated into an intra-ocular implant for epi-retinal stimulation. Other groups working on sub-retinal implants [6, 7] have also inherently (as part of the electrode – photodetector design) investigated similar stimulation strategies involving parallelization of sensors and associated concurrent stimulation.

The need to investigate concurrent stimulation has been driven by the increasing recognition that to create a device capable of effectively simulating prosthetic vision, will require electrode numbers and transcutaneous communications protocols that far exceed that possible with a serial mode of electrode stimulation.

There is a paucity of data on the effects of interaction between multiple current sources in either physiological saline or in excitable tissue. In this paper we shall model the electrical charge distribution under circumstances of multiple current injection sites for various electrode configurations, including simple electrode pairs and then a more complex electrode array designed based on a hexagonal lattice [4]. These rudimentary simulations highlight the significance of the interactions between multiple current sources and the importance of electrode design in minimizing undesirable cross-talk.

## II. METHODS

A 2D computational model was developed to simulate the distribution of voltage arising from multiple parallel current sources connected to an electrode array. Electrodes within the array were designated as either injecting or return (guard) electrodes, whereby injecting electrodes were connected to one of a number of current sources and return electrodes were connected to zero potential. The model was formulated using either pairs of cylindrical electrodes of radius 0.2 mm and height 0.2 mm arranged in different orientations, or a hexagonal lattice of 98 electrodes immersed in a thin volume of physiological saline measuring  $20 \times 20 \times 0.2$  mm.

With this geometric arrangement being symmetric in the third z-dimension, the problem reduces to solving a 2D system. The Poisson governing equation for the voltage distribution,  $V$ , throughout the saline region was

$$-\nabla \cdot (\sigma \nabla V) = I \quad (1)$$

where  $\sigma$  is the conductivity of the medium and  $I$  is the volume current density injected into the medium at the given location [8]. For physiological saline,  $\sigma$  was taken to be 1 S/m [9]. Capacitive effects of the electrode-electrolyte bilayer were ignored.

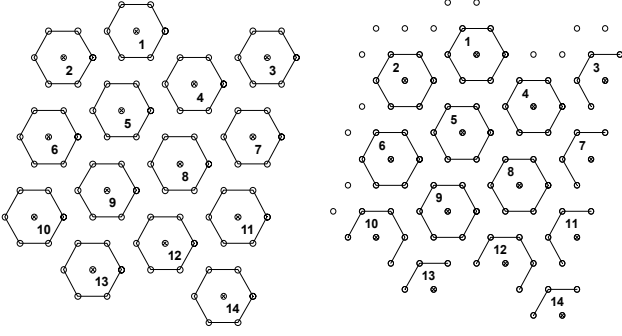


Figure 1. Hexagonal electrode array with 14 parallel current sources comprising a central injecting electrode and six return electrodes (left panel) acting as guards. In the right panel, the central electrode for each hexagonal cluster has been translated downwards and to the right. This leaves a number of the current sources (to the bottom and right of the electrode array) without a full complement of six guard electrodes.

Using cylindrical electrodes and constant  $\sigma$ , equation (1) reduces to the 2D partial differential system

$$\frac{\partial^2 V(x, y)}{\partial x^2} + \frac{\partial^2 V(x, y)}{\partial y^2} = \frac{-i_s^n}{\sigma \pi r^2 h} \quad (2)$$

within the  $n$ th stimulus electrode

$$\frac{\partial^2 V(x, y)}{\partial x^2} + \frac{\partial^2 V(x, y)}{\partial y^2} = \frac{i_r^m}{\sigma \pi r^2 h} \quad (3)$$

within the  $m$ th return electrode

$$\frac{\partial^2 V(x, y)}{\partial x^2} + \frac{\partial^2 V(x, y)}{\partial y^2} = 0 \quad (4) \quad \text{outside}$$

all electrodes, and

$$V(x_c, y_c) = 0 \quad (5)$$

at all return electrode center coordinates  $(x_c, y_c)$ .

$i_s^n$  is the absolute value of current injected into the  $n$ th stimulus electrode,  $i_r^m$  is the absolute value of current returned from the  $m$ th return electrode, and  $r, h$  are the radius and height of the electrode cylinders. In general, the  $i_s^n$  currents injected are given, whereas the return currents  $i_r^m$  are unknown when there is more than one return electrode. These return currents can be determined from the additional constraint given by equation (5). Zero-flux boundary conditions,  $\frac{\partial V}{\partial x} = 0$ ,  $\frac{\partial V}{\partial y} = 0$ , were imposed on the edges of the domain.

A custom spectral collocation method implemented in MATLAB (The MathWorks Inc.) was used to solve the system of equations. Small rectangular regions were used to segment the 2D domain. These regions enclosed each circular

electrode as well as the spaces between electrodes and between electrodes and the domain boundary. Within each segment, a non-uniform x-y mesh was generated using Chebyshev node spacing [10] in order to achieve a more dense packing of nodes near each segment boundary compared with the centers of each segment. First-order derivative continuity in voltage was enforced at each segment boundary.

Inverting the system of differentiation matrices allowed the voltage at each node to be calculated. Instead of using finite-difference approaches, spectral differentiation was used. This allowed for more accurate derivatives with fewer nodes [11]. For the simulations presented here, 7 nodes were placed in each x,y position within all electrodes, 9 nodes in the inter-electrode spaces, and 23 nodes between the outermost electrodes and the boundary of the domain. That is, a total of  $219 \times 331$  nodes in x and y respectively.

In the electrode pair simulations, injecting and return electrodes were always separated by a distance  $p$  of 1 mm. These pairs were then arranged in-line (zero degrees) in the x direction or orthogonally (ninety degrees) in the y direction and separated from 1 mm to 6 mm in 1 mm increments.

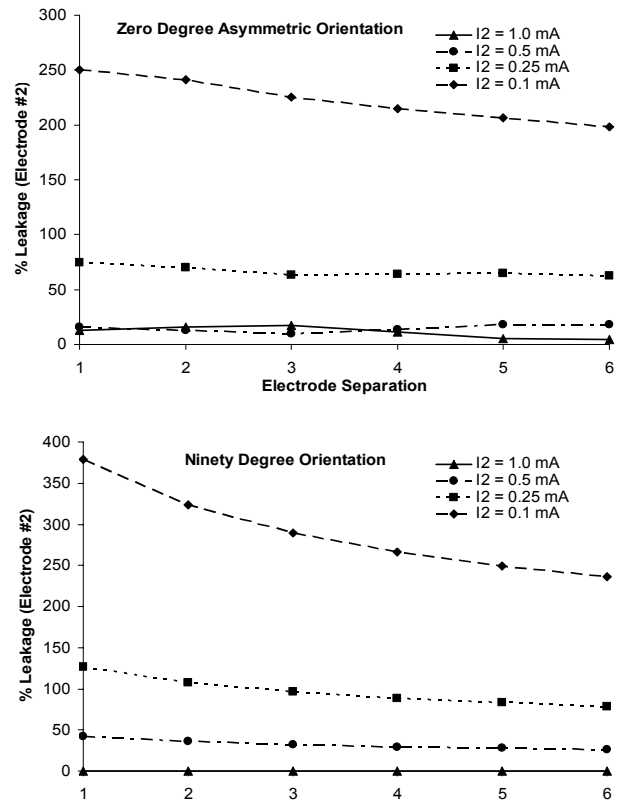


Figure 2. Leakage in second return electrode when injecting concurrently into two separate electrodes arranged in different orientations. Electrode separation in mm.

In the first electrode pair, 1 mA was always injected. In the second pair, simulations were performed with injections of 1, 0.5, 0.25 and 0.1 mA. The current ‘leakage’ in the second return electrode was calculated as the percentage deviation from the nominal injected current. Thus if 0.5 mA was injected but 0.6 mA returned due to cross-talk from the first electrode pair, then the leakage would be 20%.

In the second set of simulations, a hexagonal arrangement of an electrode array is simulated in two different configurations (Figure 1). Each injecting electrode is surrounded by up to six guard electrodes. These configuration changes relate to the fact that using the hexagonal construct, it is possible to relocate the origin of the injecting electrodes to one of seven unique positions.

### III. RESULTS AND DISCUSSION

Figure 2 demonstrates simulation results from the electrode pairs. Note that as expected with a ninety degree orientation and equal currents of 1 mA injected, the leakage is zero. However, if the injected currents are not identical then the return electrode (associated with the injecting electrode that has the lower current), receives considerably more current, particularly at closer separations.

Table 1 lists the return currents (calculated by summing respective guard currents) from the 14 separate current sources. In the case of a single guard there is much greater deviation in current across the 14 sources (range from 0.68 to 1.39 mA) in comparison with using a hexagonal guard arrangement (Figure 3). Translating the origin of the hex cluster also has an observable yet less significant effect.

These current imbalances are obviously of considerable importance when trying to accurately inject and recover charge from various regions of the neural retina.

Table 1. Return (guard) currents (mA) calculated for each current source in three different electrode configurations. Two of these are detailed in Figure 1 and the third option is where a single return (immediately to the right of the injecting electrode) is used.

Hexagon	Single Return	All Guards	Translated Guards
1	0.988	0.997	1.013
2	1.258	1.073	1.084
3	0.745	1.003	0.901
4	0.843	0.961	0.970
5	1.119	0.880	0.880
6	1.304	0.998	1.014
7	0.683	0.998	0.987
8	0.964	0.833	0.839
9	0.967	1.065	1.078
10	1.394	0.977	0.996
11	0.693	0.970	0.995
12	1.004	0.997	1.118
13	1.171	1.030	0.807
14	0.810	0.993	1.029
Mean	0.996	0.984	0.979
SD	0.221	0.061	0.089

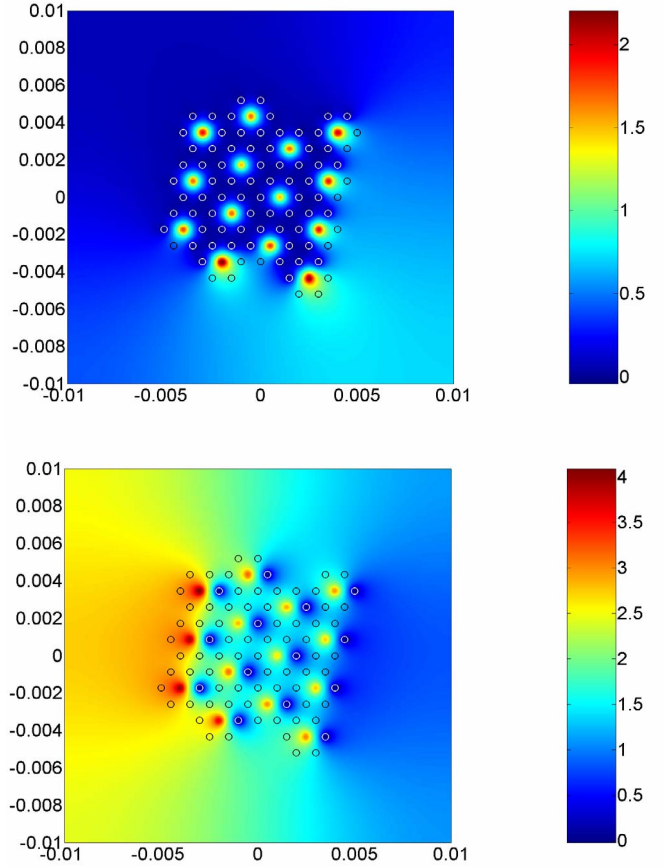


Figure 3. Voltage gradients for the hexagonal electrode array immersed in physiological saline.  $x$  and  $y$  axes are in mm. Top panel is simulation for all guards in a translated hex cluster as in Figure 1 (right panel). Bottom panel is the simulation with a single return electrode to the right of each injecting electrode. Active return electrodes are drawn as white circles and inactive returns as black circles.

### IV. CONCLUSION

Despite intense research in retinal prosthesis, there is very little published on concurrent stimulation of excitable tissue. While the models presented here are rudimentary, work in progress is to marry the models of current injection with neural models of retinal tissue to create a bidomain model capable of simulating activation of retinal ganglion cells. With further modeling of distant returns, the possible benefits of monopolar versus bipolar stimulation could also be investigated.

Even without this more detailed modeling, the current study suggests that bipolar stimulation using hexagonal guard electrodes warrants continued investigation in order to optimize the design of both the stimulating electronics and electrode arrays.

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