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MODEL AND COMPUTER SIMULATION FOR PRECISION CONTACTLESS ANALGESIA

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Introduction

The object of this work was to develop a mathematical model and subsequent computer simulation for a technology that can provide neural blockade in a contactless form. It is known from earlier work that providing an electrode proximate to a neuron will create an electrical field that can either hyperpolarize or depolarize a neuron. The object was to demonstrate that this same effect could be created in a contactless way. This could be accomplished by creating a magnetic coil attached to a circuit providing a time varying current. Figure One shows a schematic of the coil in a plane parallel to a nerve lying 3 cm below it. The object labeled 13 is the circuit, 12 is the coil and 10 is the
nerve below it. This study was designed to demonstrate that this magnetic coil could create an external electrical field which could block action potentials transmitting pain. In order to block the action potential from propagating, the interior of the cell must be sufficiently hyperpolarized so that the action potential with positive 40 mv depolarization cannot bring the cell to -60mv. Thus the interior should be hyperpolarized to greater than -100mv. Therefore the hyperpolarization produced by the external magnetic flux should be -30 mv or more. This then would cause a nerve block.

Materials and Methods

IRB: This study only consisted of mathematical computer simulations and is exempt from IRB review as per NYU Langone policy. (numbered equations in this section are shown in Table One) The model for electrical conduction in the neuron which has been widely accepted is the modified cable equation (Table One Eqn. 1) The mathematical model was constructed to model an electrical coil connected into an RLC circuit with a time varying current in the coil. The coil is placed in a xy plane parallel to a plane localizing a peripheral nerve. The time varying current leads to either an expanding or contracting magnetic field creating a secondary electrical field (Table One Eqn.2).

For the case of the coil with a time varying current, such as a coil in the present study, the equation for the induced magnetic vector potential has been described (Table One Eqn.3). The equation simplifies to Equation 4 in Table One, where k is defined in Table One Eqn.5. E and K are the elliptic integrals of this variable k. Then the expression for the magnetic vector potential is used for the electric field along the axis of the axon 12 (y component Figure One) The axial electric field gradient is the source term in the modified cable equation (Equation 1) for nerve conduction.

Referenced Publications describe the solution of the modified cable equation. In this method the nerve is divided into N compartments and modeled as a lumped circuit. The axial current in each compartment is secondary to two factors. The first is the voltage gradient along the nerve. The second is the extrinsically induced electric field from the external magnetic field. The current can be related to these electric potential terms by Ohm's Law. This is applied to all nodes. Each node is successively treated as the center node with the exception of the two terminal nodes. (Table One Eqn.6). Thus there are L equations in L unknowns. The unknowns are the externally induced transmembrane potentials located in the vector V =(V1,V2,V3,..Vl). The internodal potential differences are due to the external electric field: E={E1,E2,E3,E4....EL). The equations are expressed as the matrix product of the matrix: A which contains the coefficients for V1,V2... and the product of the matrix: B which contains the coefficients of E1,E2,E3....leading to the following
equation: A x V= B x E. Then V can be solved for: V = B(inv) x E . This provides the value of V, the transmembrane voltage, over the entire length of the nerve. A computer program was written to run in the Octave environment(Linux analogue to MATLAB) on a Intel corei5 motherboard running LINUX OS UBUNTU 20.04. to calculate the externally induced transmembrane potentials in the subthreshold condition.

Results/Case Report

The following parameters for the RLC circuit and coil will enable production of sufficient transmembrane voltage to produce blockade of a neural impulse. The following example illustrates the set of conditions which produced the desired effect:

rc=radius of coil = 1 cm
rw=radius of wire = 1mm
Resistance R=0.16 ohms
Capacitance C= 0.0007 Farad
Inductance of coil = L= 9e-5 Henry
Voltage=Vo=1700 volts
z0= height is coil above axon = 3 cm

Figure 2. shows the calculated externally induced transmembrane potential along the length and cross section of the nerve using the preceding coil and circuit values. The time is 60 microseconds from the application of 1700 volts dc across the circuit. The surface plot of the induced transmembrane potential is shown in nerve tissue lying 3 cm below the coil. The x and y axes represent all points in that plane.

Discussion

From examination of the graph in Figure 2 it can be seen that there is a maxima and a minima in the transmembrane potential. The minima correspond to hyperpolarized points. To block propagation of neural impulses these points have to have an induced transmembrane potential more negative than -30 mv. It can be seen from the graph that this condition is met at multiple locations along the length of the nerve. In that case the net transmembrane potential at these points will be greater than -100 mv and thus cannot be depolarized by an advancing action potential. As the minima get closer
and closer to -30 mv the range of x values(along the cross section of the nerve), for which the induced transmembrane potential is sufficient to cause neural blockade can be made very small. Therefore this provides focused pain blockade.

References

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Disclosures

No

Tables / Images

Figure 1

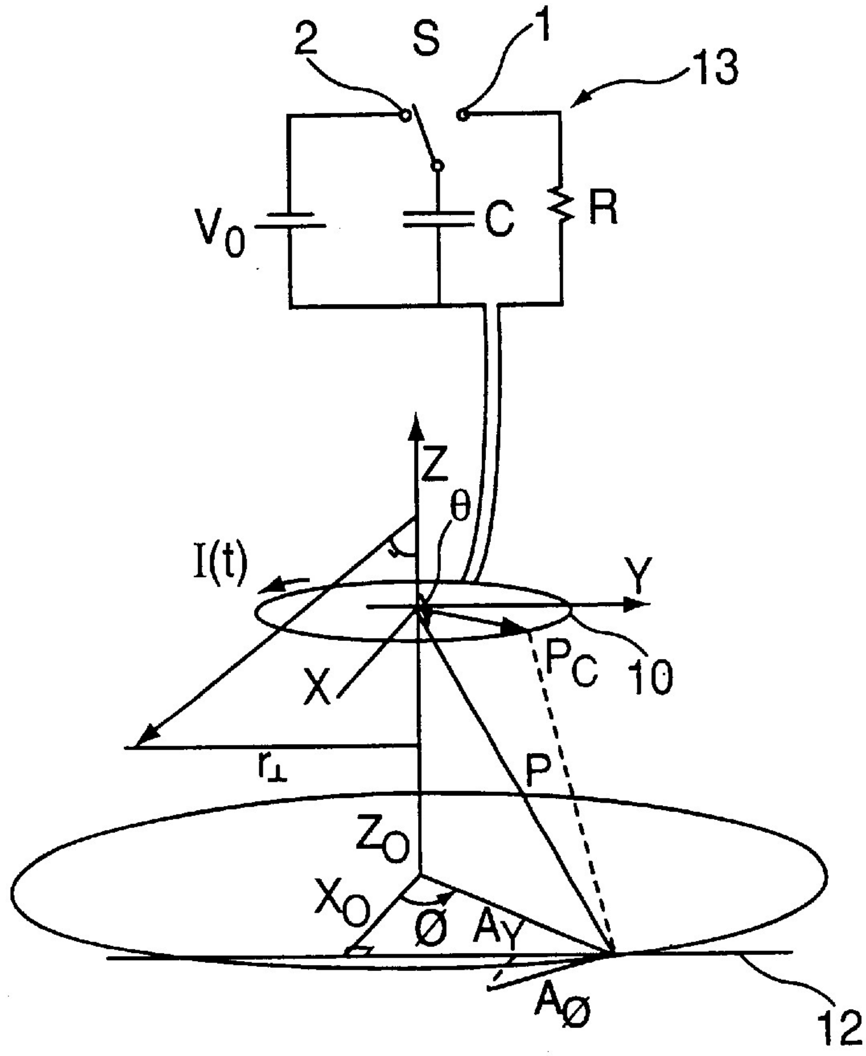

TABLE ONE

EQUATION NUMBER	EQUATION	VARIABLES
1	$\delta^2 \frac{\partial^2 V}{\partial x^2} - V - \alpha \frac{\partial V}{\partial t} = \delta^2 \frac{\partial E_x}{\partial x}$	where: V represents voltage, t= time x= axis of neuron $\delta = space\ constant$ Ex =electric field
2	$E = -\Delta\varphi - \frac{1}{c}\frac{\partial A}{\partial t}$	E = electrical field A= magnetic vector potential leading to magnetic field
3	$\frac{A}{c} = I(t)\ \frac{\rho c\mu}{\pi}\int_{0}^{2} \frac{\pi cos\varphi d\varphi}{\sqrt{((\rho c)^2 + \rho^2 - 2\rho\rho c sin\theta cos\theta)}}$	
4	$A = \frac{4I\rho c}{c\sqrt{(\rho c^2 + \rho^2 + 2\rho\rho c sin\theta}}\left[\frac{(2-k^2)K(k) - 2E(k)}{k^2}\right]$	E and K are the elliptic integrals of this variable k
5	$k^2 = \frac{4\rho\rho c sin\theta}{\rho^2 + \rho c^2 + 2\rho\rho c sin\theta}$	
6	$V_{n+1} = \left(\left(\frac{G_m}{G_a} + 2\right)V_n\right) + V_{n-1} = \int_{(n-1)dl}^{(n+1)dl}(E_x)dx - \int_{(n-1)dl}^{(n)dl}(E_x)dx$	Where :n= 2,3,4,...L-1 dl= the internodal distance L = the total number of nodes dx=lengthincrement along axon Gm=membrane conductance Ex is the axial component of electrical field