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Design and Simulation of an Acoustic Micro Prob Made of Piezoelectric Materials to Stimulate Nerve Tissue and Generate Action Potential

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***Abstract*— In this study , design and simulation of an acoustic micro probe which is employed to form controlled ionic beam inside axoplasm of an axon have been explored . the probe is made of piezoelectric material . this beem is designed so that it can stimulate a nerve to generate action potential . the simulation has been performed by using the Comsol Multiphysics 3.5a software . In this simulation we have designed a piezoelectric blade that part of it is placed in an ionic environment . By applying an external voltage to the other side of the blade and due to the properties of piezoelectric materials, the blade will vibrate. This vibration causes the displacement of the ions in the ionic environment and leading to the produce current . By applying the current that obtained to** FitzHugh-Nagumo model of nerve, which is models the excitable site of axon **, Action potential inside of the axon will be produced and propagated . the simulation results show the feasibility of method and its corresponded conditions .**

Keywords*— *Action potential; Axon; Piezoelectric; Fitzhugh-Nagumo equations

I.INTRODUCTION

The Nerve is the most important part of the nervous system that as communication and control network between different parts of the body . The human nervous system consists of billions of nerve cells or neurons . Each neuron has a cell body or Soma (the merger), dendrites (the receiver) and an axon (nerve message transfer part) and the synaptic terminals. Nerves in the collection known as the nervous system are connected and transmit data through the action potential. An action potential is a rapid changes in the membrane potential that spread rapidly along the nerve fiber membrane. Each action potential begins with a sudden change from the normal resting negative membrane potential to a positive potential and then ends with an almostequally rapid change back to the negative potential. To conduct a nerve signal, the action potential moves along the nerve fiber until it comes to the fiber's end. [1] .

In 1952 , Hodgkin and Huxley provided a mathematical model to explain how to start and the distribution of the action potential in neurons that includes a set of non-linear ordinary differential equations that approximation the electric properties of excitable cells, such as neurons and cardiac muscle cells . Hodgkin and Huxley by presenting this model, received the Nobel Prize in Physiology and Medicine in 1963.

According to the above description , We have shown that we can design a acoustic micro-probe and applying an external voltage to stimulate nerve tissue , an acoustic wave created. Then by applying the wave generated as input to simplified Hodgkin Huxley equations, action potential produce and propagate inside of axon .

II.PIEZOELECTRIC EFFECT

The piezoelectric effect is a property that exists in many materials. The name is made up of two parts; piezo, which is derived from the Greek work for pressure, and electric from electricity. The rough translation is, therefore, pressure - electric effect. In a piezoelectric material, the application of a force or stress results in the development of a charge in the material. This is known as the direct piezoelectric effect. Conversely, the application of a charge to the same material will result in a change in mechanical dimensions or strain. This is known as the indirect piezoelectric effect [2].

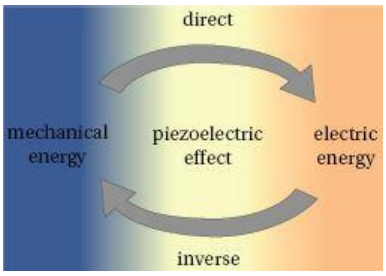

Fig 1. Piezoelectricity enables conversion frommechanical energy into electric energy and vice versa [3]

Nowadays the piezoelectric effect is useful in many applications that involve electronic frequency generation ,the production and detection of sound, generation of high voltages, microbalances, lighters, loudspeakers, signal transducers and etc.

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III. FITZHUGH-NAGUMO MODEL

The analysis of the Hodgkin Huxley equations in extremely difficult because of the nonlinearities and large number of variables . mathematical analysis would be helpful if it is performed on simpler equations whose solutions shared the qualitative properties of those of the Hodgkin Huxley eqations. analysis of such simpler systems may lead to the discovery of new phonemena,which may be searched for in the orginal system and also experimental preoparations. Such a simplified system of equations has its origin in the work of Fitzhugh and Nagumo and is known as the Fitzhugh Nagumo equations[4].

In other word, The Fitzhugh-nagumo equations is a simplified form of the Hodgkin-Huxley model for electrical activity in a neuron, in this model a neuron can be stimulated with an input such as an electric current . the state of this excitation is described by variable u_1 which represent the voltage (excitation) in the neuron as a function of time . when a neuron is excited, physiological processes in the cell will cause the neuron to recover from the excitation . the variable u_2 in the model equation represents this recovery[5] .

The equations are given by :

$$\frac{\partial_{u_1}}{\partial_t} = \Delta u + (\alpha - u_1)(u_1 - 1)u_1 + (-u_2) + I \qquad (1)$$

$$\frac{\theta_{u_2}}{\theta_t} = \varepsilon(\beta u_1 - \gamma u_2 - \delta) \qquad (2)$$

α is the excitation threshold and ε is the excitability. β, γ and δ are parameters effecting the resting state and dynamics of the system [6].

IV. SIMULATION WITH COMSOL MULTIPHYSICS

One of the most powerful software in analysis and simulation the finite element method (FEM) is Comsol Multiphysics . In recent years, a wide variety of simulation processes including micro electro mechanical systems has been developed. This software has several characteristics that the calculation accuracy and speed can be noted. The most important steps in the comsol software simulation can be selection of the module, space dimension, geometry, boundary conditions, materials description, mesh generation and choose the type of analysis pointed out. The following describes the steps we expressed .

Before start designing, an essential point, that is, in order to avoid numerical limits in the simulation, the selected values for the size of the piezoelectric blade, the Ionic environment and axons are larger than actual values we've considered to obtain more precise results are included in the simulation.

A. Select the dimension and type of modules

The first step in the simulation process, is the selection of the dimension and kind of modules. The dimension issue is due to the geometry of the model that can be one-dimensional, two-dimensional or three dimensions. In this project we have used the three-dimensional structure.The module also has been selected base on the type of issue and may be used in a simulation of one or several modules .

For this purpose, in design the piezoelectric blade, ionic environment and axons, respectively we have used from MEMS, electrostatic and PDE (general form) modules.

B.Geometry

After selecting the module, now it is time to create the various components of the geometric model. In the finite element method simulation, we try with possible geometric approximation, limit the size of the model to reduce the time required to perform the analysis.

The geometry of piezo electric blade modeled as a solid block with size of 10 ×10 ×140 m^3 (l ×w ×h) , the piezoelectric blade is made of Lead zirconate titanate that it is known PZT. the blade is connected to a voltage source we have. The other side of the blade is placed in the ionic environment. Since the ionic environment should be similar to the human body and the space around nerve cells so it is made of saline matter. The ionic environment is assumed a solid block with size of 5 ×1 ×40 m^3. Also to simulate the axon , we have used from Simplified hodgkin-huxley equation . The axons geometry is a hollow cylinder with length of 120 m and radius of 5 cm .

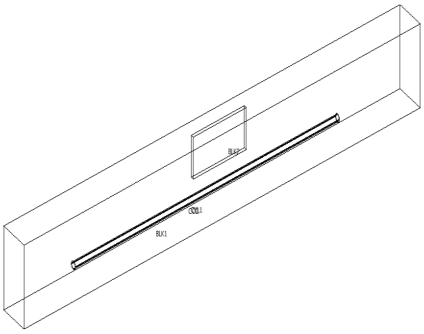

Fig 2. Geometrical model for simulation

C.Subdomain Settings

In this section , for completing the piezo module subdomain setting, due to use titanium lead zirconate, comsol default setting for this material was used. so that the density of this matter is equal to 7600 [kg/m^3].

In the electrostatics module , the equation that used for ionic enviroment is as following .

$$-\nabla . \varepsilon_0 \varepsilon_r \nabla V = \rho \qquad (3)$$

Where V is electric potential, ε_r is the relative permittivity, ε_0 is the permittivity of vacuum and ρ is the charge density.An important point that should be considered is the saline relative permittivity and it is equal to 80.

in PDE module, the axon subdomain described by two dependant variables , u_1 and u_2 . the equation that solved by PDE mode is as following .

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$$e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla \Gamma = F \qquad (4)$$

where e_a is mass coefficient, d_a is damping coefficient, Γ is numerical flux and F is source term . in order to create the main equations ie (1) and (2) equations, we need to following parameters .

$e_a = 0$, $d_a = 1$, $F = 0$

The numerical flux Γ for equation (1) and (2) is set to:

$$\Gamma = \Delta u + (\alpha - u_1)(u_1 - 1)u_1 + (-u_2) + I \qquad (5)$$

$$\Gamma = \varepsilon(\beta u_1 - \gamma u_2 - \delta) \qquad (6)$$

Boundary conditions for the axons as well as the following :

$$u_1(t_0) = V_0.((x + d) > 0).(z + d > 0) \qquad (7)$$

$$u_2(t_0) = nu_0.((-x + d) > 0).(z + d > 0) \qquad (8)$$

D.Boundary Conditions

After determining the border areas of piezoelectric blade and applying voltage to the outer area, its time to determin the boundary areas within ionic enviroment and axon. Electric potential distribution in the ionic environment is done by using electrostatic module and Maxwell's equations .

Nonlinear differential equations or Fitzhugh-nagumo as axons describe the cell membrane behavior with respect to the input that we applied to them . All of the axon boundaries in the PDE mode are taken as Neumann boundary condition and the equation that used in boundary mode is as following :

$$-n.\Gamma = G \qquad (9)$$

Where Γ is numerical flux and G is source term. Γ from Equation (5) is obtained and G = 0 . all boundaries of ionic environment are at ground potential (V = 0),also all boundaries of the axon are selected as electrical potential with the coupling variable u_1=V_0

E. Mesh Generation

The most important part of simulation in comsol software is mesh generation. Generally the software comsol, first divide the model into smaller parts and solve the problem for every components, and then extended to the whole issue.

In the mesh generation, the size of different elements should be considered carefully as to reduce the size of elements, the increased number of elements result in increased accuracy and computation time. By increasing the accuracy of the elements, the computation time is reduced .

In this paper, according to the type of simulation and conditions, we have used the triangular elements in the model. The reason is that by using the triangular elements, solving the problem is rised quickly. In axons mesh generation also have been tried to use smaller elements in sensitive areas such as axons and piezoelectric blade common border. 19,837 is the number of elements used. To solve this problem, a static analyzer is used. Further , In order to consider the dynamics of the action potential, the solution of the time dependent and Direct (SPOOLES) System is used.

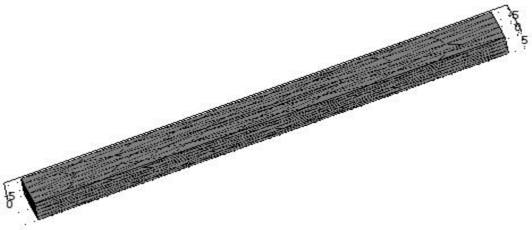

Fig 3. the meshed model

V.POST PROCESSING

By applying the above steps, you can choose domain plot prameters from the Postprocessing menu and Select the initial and final regions of axons, then see the result of waveform the action potentials simulation in axons.

Figure 4 shows the beginning and end of the action potential in the axons . Figure 5 shows the membrane potential change as a voltage pulse along the axon .

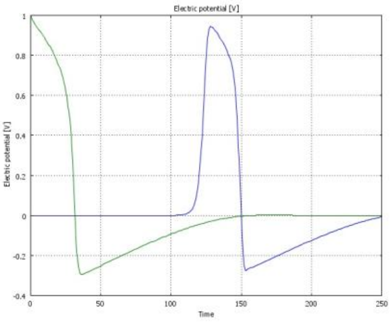

Fig 4. Action potential in the axon at the starting (green) and the ending points (blue) of the axon .

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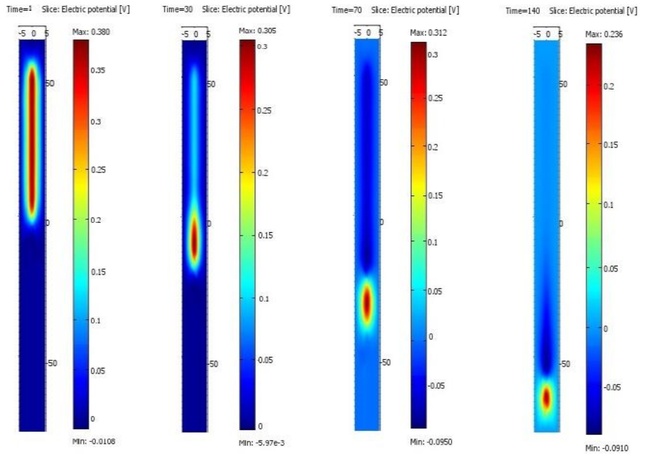

Fig 5.Electric potential on a slice of axon at times (a) 0sec, (b)30sec, (c) 70sec and (d)140sec with.0.380 V(Max) and 0.236 V(Min).(from left to right)

VI.CONCLUSION

In this paper, by applying a voltage to the piezoelectric blade that part of which is located within the ionic enviroment, acoustic waves were provided within this environment. With the release of radiation into the environment ionic particles start to move and creating an electrical signal. The electrical signal is created from the electric charges of the ions is due to the electric field. By creating this field, the ion current in this environment is appeared. Then we apply this current as input to simplified Hodgkins Huxley equations and it is observed that the action potential wave is generated inside of axons and propagate at different times along the axon . In this way, by designing a piezoelectric blade and with applying external voltage to it, we could produce the action potential inside of axon and propagate along it .

ACKNOWLEDGMENT

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Appendix

Table 1. Values of the parameters that used in Fitzhugh-Nagumo equations

Name	Value	Describtion
α	0.1	Excitation threshold [V]
β	0.75	System Parameter
γ	1	System Parameter
δ	0	System Parameter
ε	0.01	Excitability
Vo	1	Electric potential
nu0	0.025	Relaxtion value
d	1	Off-axis shift distance [m]

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