Optimizing the Material, Inter-distance and Temperature Effect of Intramuscular Electrodes used to Stimulate the Thoracic Diaphragm

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***Abstract*—The technique of electrically stimulating the thoracic diaphragm is conducted by implanting a diaphragmatic pacemaker, in which the phrenic nerve is stimulated, resulting in stimulating the diaphragm. A diaphragmatic pacemaker is usually implanted for a long period of time. Intramuscular electrodes can be used for stimulating the diaphragm, for such conditions in which phrenic nerve stimulation cannot be done. The material and inter-distance of the stimulation electrodes are very important in order to stimulate the diaphragm in efficient manner. This paper explains the Optimization of material, inter-distance and temperature effect of intramuscular electrodes used to stimulate the thoracic diaphragm. A model has been constructed and simulated on the software COMSOL Multi-physics, whose results shows that the threshold muscle stimulation is achieved when 1 volt is applied at the electrode, 15 cm apart from each other. The result further suggested that this kind of electrical stimulation cannot produce significant thermal effect on the tissues.**

***Index Terms*—COMSOL Multiphysics, current density, diaphragmatic pacemaker, diaphragm pacing, intramuscular electrodes, thoracic diaphragm.**

I. INTRODUCTION

Thoracic diaphragm is an internal skeletal muscle which spreads at the end of the rib cage. Diaphragm is used to separates the thoracic region from the abdominal region. It plays an important role during the process of respiration. The contraction of diaphragm increase the volume of thoracic cavity and air enters into the lungs. When the diaphragm relaxes, the volume decrease and the pressure increase so that air can be exhaled out. The diaphragm help in the process of respiration, it also assists in other processes, like taking the urine and feces out of the body. This is done by increasing the pressure of the abdominal cavity.

The diaphragm receives and sends the motor and sensory information, through the phrenic nerve. If patients are suffering from spinal cord injuries or diaphragm paralysis, diaphragm/phrenic nerve pacing is necessary for them. The process of diaphragm pacing is done by implanting a diaphragmatic pacemaker inside the patient. This is a surgical process in which electrodes are implanted around the phrenic nerve in the cervical or thoracic region.

The researchers, James S. Walter, et. al. has stated in his work [1], that for the process of diaphragm pacing, the diaphragm itself can also be stimulated, using intramuscular electrodes. In his work, his main emphasis is upon the stimulation of the intercostal and abdominal muscles and the diaphragm using polypropylene anchors. But the current density of the electrodes for providing sufficient contraction and relaxation has not been mentioned.

In the Karlsruhe transactions on biomedical engineering, volume 15, Julia Bohnert [2], has mentioned her study upon the effects of time-varying magnetic fields in the frequency range 1 kHz to 100 kHz upon the human body, in which many dielectric properties within a human body have been observed, which includes the resulting current densities within the model of the skeletal muscle. Their main emphasis is the change of frequencies and their effect on the human body. The amount of voltage and the distance between the electrodes, their effects on the human body's mechanism, which includes the skeletal muscle (thoracic diaphragm as well) have not been their main approach. The threshold current density to stimulate the muscle is between 2.38A/m2 and 4.45A/m2.

This paper explains the Optimization of material, inter-distance and temperature effect of intramuscular electrodes used to stimulate the thoracic diaphragm. The simulation results show that electrical stimulation of the electrodes did not produce any thermal effect in the surrounding tissues.

II. MATERIALS AND METHODS

A. Diaphragmatic pacing

The process of diaphragm/phrenic nerve pacing can be done by inserting electrodes into the diaphragm [3]. The size, inter-distance and material of electrodes are very important in order to get effective stimulation. To optimize the different parameters of the electrode a model is design using COMSOL software.

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B. Designing and the placement of the electrodes on COMSOL Multiphysics

The model of the lungs and diaphragm has been designed on the software COMSOL Multiphysics. While designing a real world system on this software, the original properties of that system are to be entered in the model.

A 2-D model has been used for the simulations. For the geometry of the lungs, the original values have been used [5]. The average length of human lung is in between 25-30 cm and the width 10-20 cm. By using the Bezier Polygon, a pair of lungs has been constructed, whose lengths are 32 cm, and widths are 20 cm.

For the geometry of the diaphragm [6], its excursion is in between 3-5 cm. This has also been constructed through Bezier Polygon and its width is 3.5 cm. For the geometry of the lungs, it should be exactly upon the diaphragm, it must not collapse. For that, the difference operation from the Boolean operation has been used, through which the lungs have been subtracted from the diaphragm and then again placed by duplicating the old ones, thus giving us the lungs exactly upon the diaphragm. Then two electrodes have been inserted into the diaphragm, 4x1 cm using the difference Boolean operation.

For the model of diaphragm the materials, Electrical conductivity [7], Relative permittivity [7], Heat capacity [8], Density [8] and Thermal conductivity [4] have been added. Similarly, for the model of lungs, the materials Electrical conductivity [7], Relative permittivity [7], Heat capacity [8], Density [9] and Thermal conductivity [4] have been added.

TABLE I
PROPERTIES OF THE MATERIALS USED IN SIMULATION.

Materials	Lungs	Diaphragm
Electrical Conductivity	0.06366 S/m	0.3621 S/m
Relative permittivity	$1.634e^4$	$3.043e^4$
Heat capacity at Constant pressure	3886 J/(kg.K)	3421 J/(kg.K)
Density	332 Kg/m^3	1041 Kg/m^3
Thermal Conductivity	0.1 W/(m.K)	0.5 W/(m.K)

Copper has been selected for the electrodes. For the electric current physics, a potential and a ground has been added, one electrode for the potential and the other one for ground. For the simulation of the model, physic of Electric current and Bio-heat transfer have been selected. Next, Stationary type of studies has been selected for the simulation.

Fig. 1 shows that how the electrodes have been placed on the diaphragm. In the similar manner, the inter-distance of the electrodes has been changed for better results.

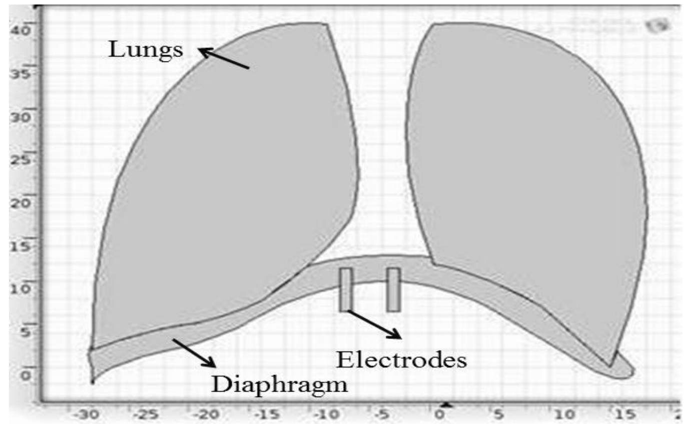

Fig. 1. Basic model used for the simulation.

C. Simulations for optimal parameters of Electrodes

Mainly three type of simulation has been done in order to find the optimal parameters of the electrodes. The first simulation is performed to find the optimal voltage of stimulation electrode used to stimulate the diaphragm. If the potential of the electrode is increased it might damage the diaphragm or the surrounding tissues. The second simulation is done in order to find the optimal inter-distance between the electrodes. If the inter-distance in not at its optimal level the electrodes electric field can affect the performance of other tissue. The third simulation is done in order to check the effectiveness of the electrodes made up of different materials. Fig. 2 shows the simulation for the voltage optimization of the electrode.

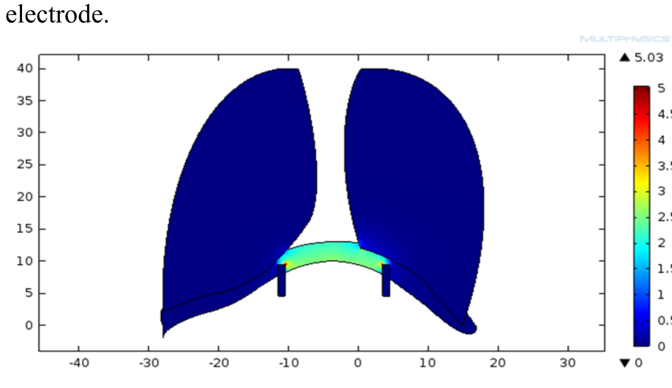

Fig. 2. Simulation for the voltage optimization of electrodes

D. Simulations for thermal effect of Electrodes

Simulations are also performed to check the thermal response of the electrodes. When the electrodes are stimulated the temperature of the electrode rises from the normal temperature. If the temperature of the electrode is significantly increases it could damage diaphragm or the surrounding tissues. The temperature effect is also simulated while changing the inter-distance of the electrodes. Fig. 3 shows the thermal effect of the electrodes.

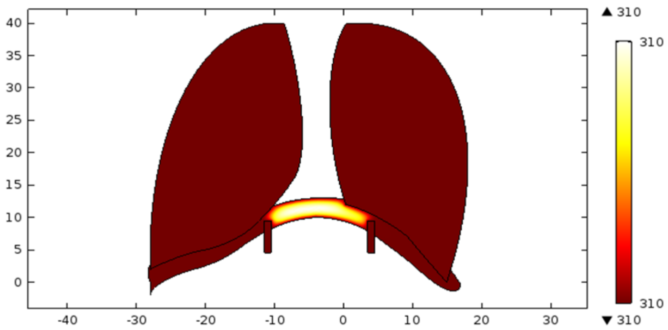

Fig. 3. Thermal response of the electrode.

III. Results and Discussion

A. Simulation results of Voltage optimization.

Fig. 4 shows the simulation result for the voltage optimization of the electrodes. From the figure is has been observed that as the voltage increase the current density at the diaphragm is also increase. The threshold current density to stimulate the muscle is 2.3 A/m2. The result shows that at one volt the current density reached the threshold level of muscle stimulation. If the increase the voltage the current density also increase at 2.5 volt the current density is about 6 A/m2. This high level of current density could affect the surrounding tissue. So according to the simulation results the optimal voltage is one volt dc for the stimulation of thoracic diaphragm.

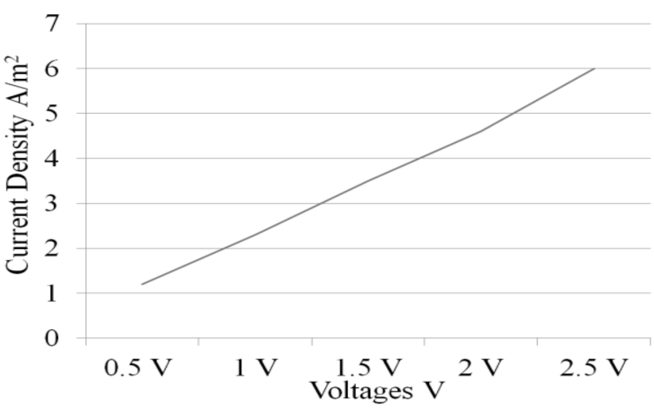

Fig. 4. Simulation result of the voltage optimization of electrodes

B. Simulation results of the optimum electrode inter-distance

Fig. 5 shows the simulation result of the optimization of inter-distance between electrodes. The simulation has done by keep going the voltage at one volt. From the figure is has been observed that as the inter-distance increase the current density at the diaphragm is decreased. If the inter-distance is very short large amount of current density is delivered to the diaphragm which could produce harmful effect. The current density reaches at the muscle threshold level when the electrodes are 15 cm apart from each other.

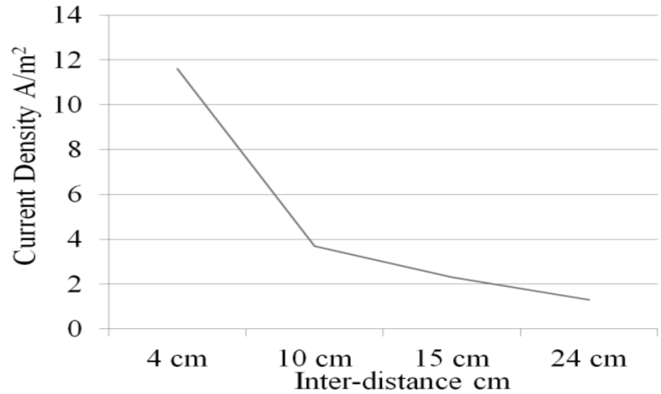

Fig. 5. Simulation result of the optimum inter-distance between electrodes.

C. Simulation results of the material optimization

Fig. 6 illustrates the simulation result of the material optimization. The results are simulated at 1 volt and having 15 cm of inter-distance between the electrodes. The result suggested that gold is the best material for electrode as it produces more current density than all other materials. It is also a known fact that biocompatibility of gold is better than other used materials in the simulation.

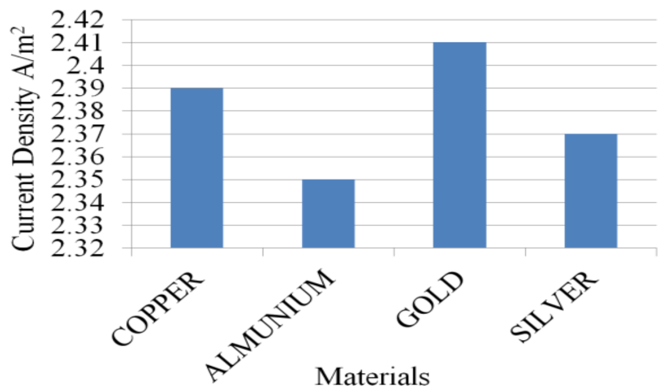

Fig. 6. Simulation result for the material optimization.

D. Simulation results of electrode's thermal response.

Fig. 7 shows the simulation result of thermal response of the electrodes when various electrical potential applied on the electrodes. The result suggested that very slight amount of temperature is increase with the electrical stimulation of the electrodes. If the electrodes are stimulated at 2.5 volt only 0.02 0K is increase from the normal body temperature.

Fig. 8 illustrates the change in temperature when the 1 volt is applied to the electrode any varying the inter-distance between the electrodes. The result suggested that is the electrodes 4 cm apart then 0.04 0K temperature is increased. If the electrodes are 24 cm apart then very negligible change is observed in the surface of the diaphragm.

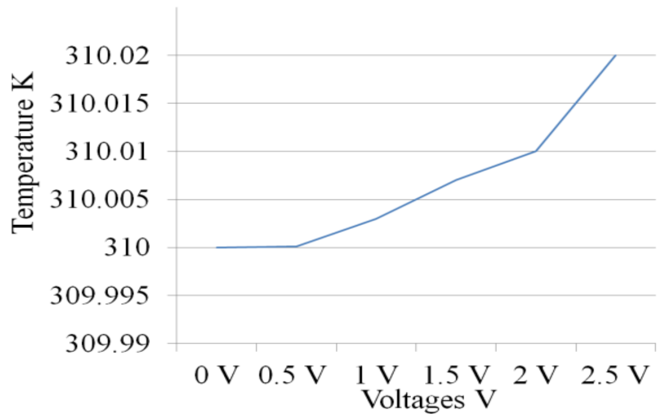

Fig. 7. Temperature response of electrode by changing electrode potential

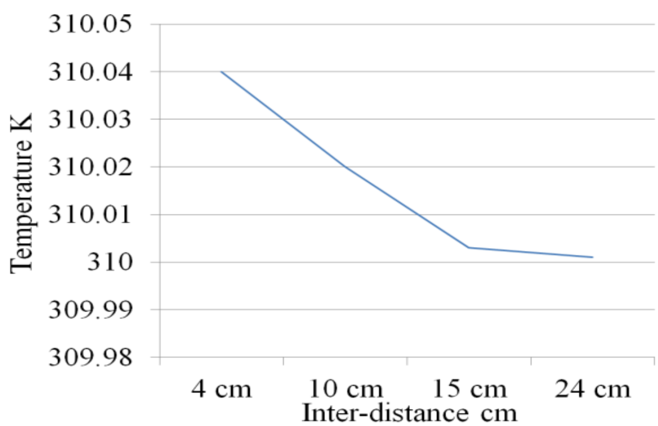

Fig. 8. Temperature response of electrode by varying inter-distance

IV. CONCLUSION

The results of the software simulation illustrate that when the electrodes are inserted with an inter-distance of 15 cm and 1 volt is provided, the current density has been observed around 2.8 A/m2. It also illustrates that when the electrodes are 24 cm apart, at 1.5 volts, the current density is observed around 2.8 A/m2, but since at lower voltage, the desired result has been observed, so that is why it is considered. The chances of muscle damage might occur at a higher voltage, since intramuscular electrodes are being used. For safety purposes, the results at 1 volt, when the electrodes are 15 cm apart are considered. This simulation results are the very preliminary research regarding electrode design for intramuscular electrodes. Further enhancements in the model are required such as covert 2-D model to 3-D for better simulation results. Shape optimization of the electrodes. The implementation of the system to perform the real world experiment, validation of the simulation results with experimental data. We believe that this simulation could serve as the basic step towards the intramuscular electrodes design for the thoracic intramuscular electrodes.

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