Design and Optimisation of Pacemaker Electrode using Finite Element Method

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***Abstract* - The optimised design and simulation of a pacemaker electrode has been presented in this paper for modelling of current distribution in human heart using Finite Element Method. The pacemaker electrode is placed inside the heart and helps to keep a normal rhythmic activity of the patient's heart. This model deals with the current and potential distribution around the pacemaker electrode and studying the effect of the electrode tip size on the current and potential distribution.**

Keywords - Current distribution, Finite Element Method (FEM), Pacemaker electrode, Potential distribution.

I. INTRODUCTION

An artificial pacemaker is a medical device that uses electrical impulses which is delivered by the electrodes to the heart muscles in order to regulate the beating of the heart. It consists of a pulse generator and one or more leads. The pulse generator is a small but sophisticated computer which is powered by a very reliable lithium battery. The leads connect the pulse generator to the inner wall of the heart with the help of small electrodes. An artificial pacemaker's aim is to maintain an adequate heart rate, either because heart's natural pacemaker is not fast enough, or there is blockage in the electrical conduction system of the heart [1]. Figure 1 shows a schematic diagram of heart with two pair of electrodes. The pulse generator unit, which is also implanted in the patient, supplies current to the electrodes.

Till now there have been three general methods that can be used for determining the pacemaker electrode's performance i.e. analytical, experimental and numerical. The analytical method provides direct analytic solution of Laplace's equation inside a body [2]. This technique is generally restricted to very simple geometries. The experimental technique is used for the measurement of parameters like current densities, voltages and other related variables in physical phantoms. This method has many limitations, one being the cost of setting up the laboratory equipment and other being the difficulty to create complex physical phantoms. Therefore simple homogenous phantoms are used [3]. The numerical methods are used to find solutions to the partial differential equations (PDE) and even the integral equations [4]. These methods are most inexpensive and flexible for providing repeatable solutions.

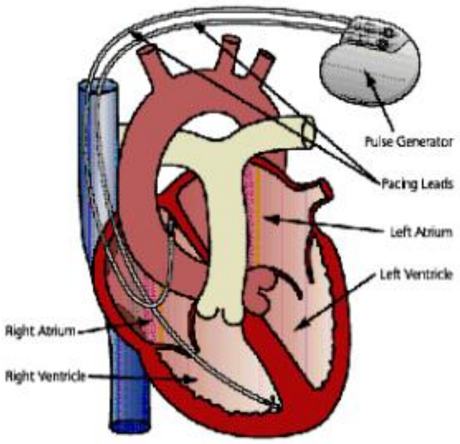


Fig. 1 : Schematic diagram of the heart showing two pairs of pacemaker electrodes.

There are many numerical methods which can be used for the solution of Laplace equation formed for analysis of the body. However keeping in view the complex domain of the body structure the finite element method overcomes the shortcomings of the other numerical methods [5] and hence been used in this paper.

Pacemakers are used for the treatment of slow heart rate disorders and help the patents to return to normal life by maintaining normal function of the heart. Kenneth Stokes [6] reviewed lead technology and described nondislodging transvenous leads and epimyocardial leads. Conductors, insulators and electrodes were also discussed. Soykan [7] obtained a piece-wise linear electrical model of bradycardia pacing leads by developing an automated modelling system. Laurent Dumas [8] considered problems associated with the positioning of the electrodes in a diseased heart and proposed a numerical approach based on the use of a cost function linked to the depolarization of the heart cells. Wei Vivien Shi [9] presented a survey on the body sensors applied in pacemakers and also discussed recent advances in modern pacemaker systems.

In this paper modelling of pacemaker electrode is done and its voltage and current distributions are studied for different size of the electrode tip.

II. METHODOLOGY

Finite element modelling (FEM) is performed for the pacemaker electrode with different tip sizes. FEM simulations are accurate and flexible for detailed studies. FEM is considered as a three step process: preprocessing (mesh generation), analysis and postprocessing. With the help of FEM a complicated problem is divided into small elements that can be solved in relation to each other. In the design and optimisation of pacemaker electrode, 3D modelling has been done which is more realistic and offers many advantages over 2D modelling.

A. Pacemaker Electrode Design

The working electrode is the hemisphere placed on the tip of the supporting cylindrical structure. The counter electrode lies in the waist of this structure. The remaining surfaces of the supporting structure are insulated. The domain of this model consists of the blood and tissue surrounding the electrode pair. Figure 2 shows the electrode in darker shade and surrounding modelling domain in lighter shade.

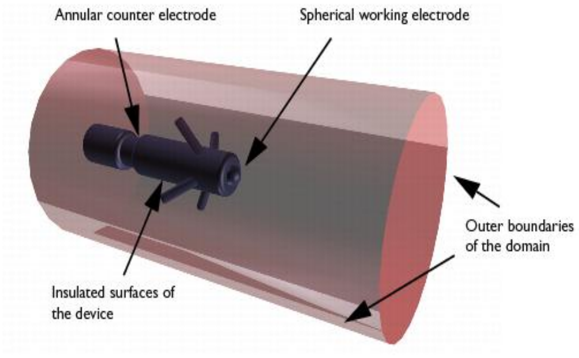


Fig.2 : Pacemaker Electrode and Surrounding Modelling Domain.

B. Domain Equations

The current in the domain is controlled by the continuity equation, which follows from the Maxwell's equations:

$$-\nabla.(\sigma\nabla V) = 0 \tag{1}$$

where σ is represented as the conductivity of the human heart. The following equations show relations between the electric potential and the field.

$$E = -\nabla V \tag{2}$$

$$J = \sigma E \tag{3}$$

C. Boundary Conditions

On the thinner waist of the electrode, ground potential boundary conditions are applied. The tip of the electrode is applied with a fixed potential of 2.8V (since modern pulse generators have 2.8V battery) [10]. The remaining boundaries are electrically insulated.

$$n.J = 0 \tag{4}$$

III. MODELLING OF PACEMAKER ELECTRODE

In this paper, 3D model of pacemaker electrode has been created for maintaining rhythmic activity of the patient's heart using Comsol Multiphysics. Modelling and simulation of various physical processes can be done by this software by solving partial differential equations. These equations are solved by finite element method. This software has various modules which are used to solve problems of particular physical domain. For this model electromagnetics module of Comsol Multiphysics is used. 3D Conductive Media DC application mode is used for the analysis of the electrode. This application mode is used in the modelling of conductive materials where a current flows because of an applied field.

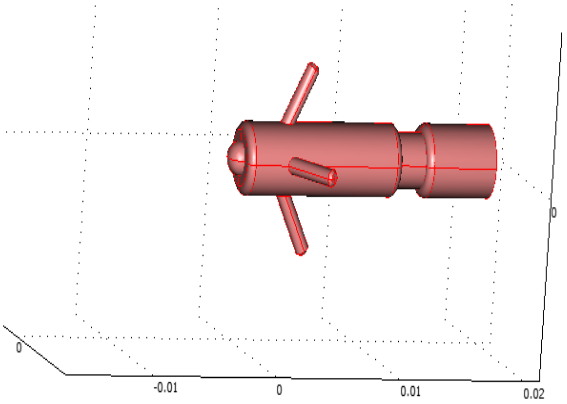
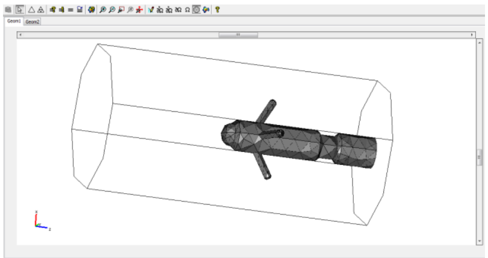


Fig. 3 : 3D model of pacemaker electrode

The 3D geometry of the pacemaker electrode is modelled as shown in figure 3 and after applying appropriate boundary conditions and subdomain settings, meshing is performed. The final meshes obtained with different free mesh parameters for different tip size are as shown in figures 4, 5 and 6.



(a) Extremely Coarse
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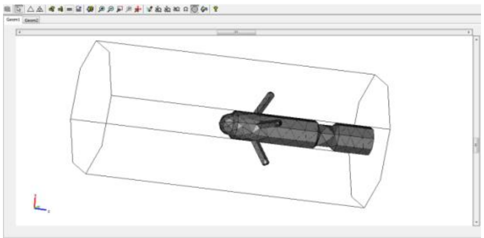
Degree of Freedom: 6959



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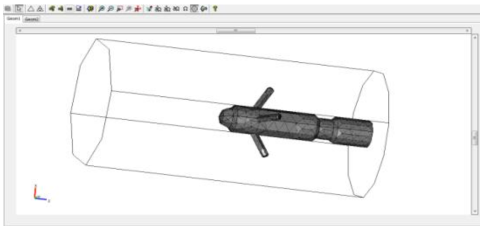

(c) Coarser
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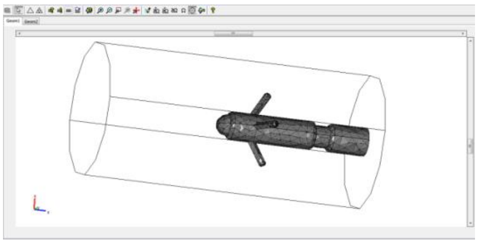

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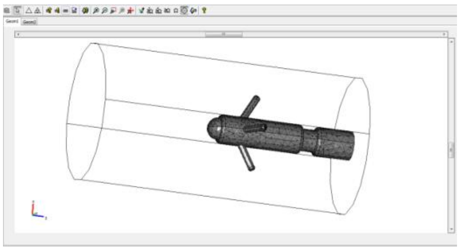

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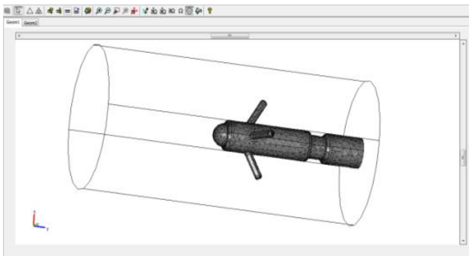

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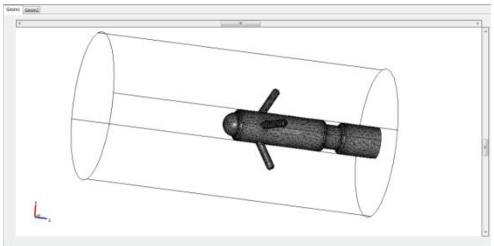

(g) Finer
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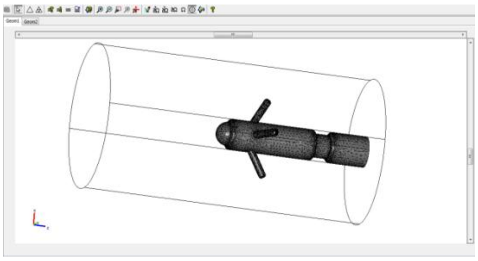
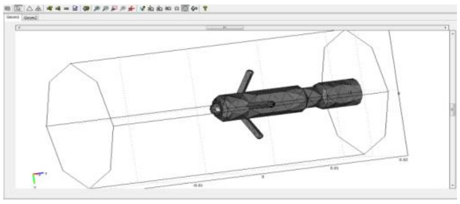
Degree of Freedom: 182450



(h) Extra Fine
Number of elements: 268886
Degree of Freedom: 384148

Fig. 4 : Mesh plots of pacemaker electrode with tip radius equal to 1.6mm



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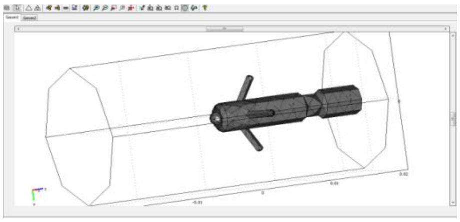

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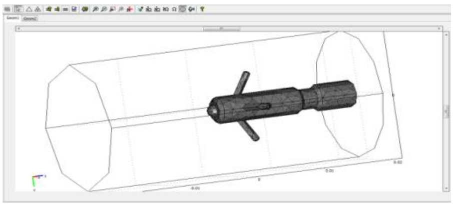

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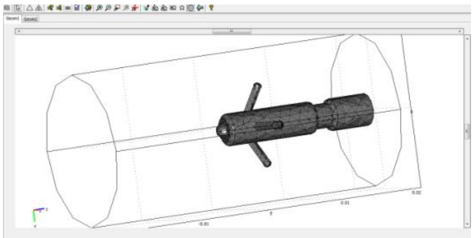
Degree of Freedom: 14417



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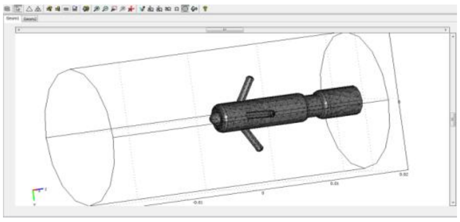
Degree of Freedom: 22778



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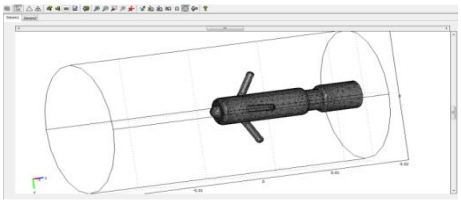

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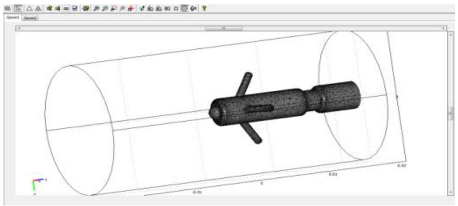
Degree of Freedom: 69159



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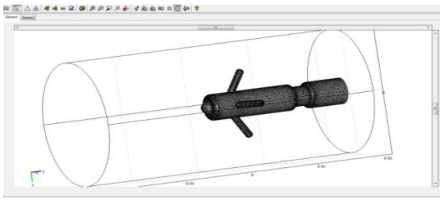
Degree of Freedom: 184484



(h) Extra Fine
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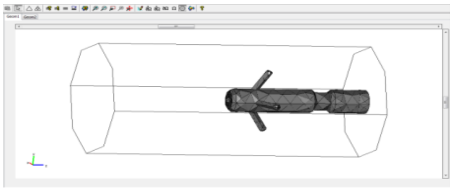
Degree of Freedom: 389418

Fig. 5 : Mesh plots of pacemaker electrode with tip radius equal to 1mm



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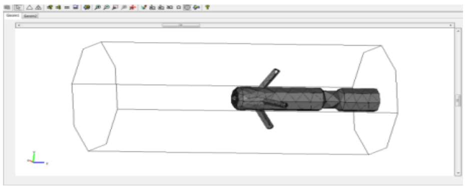

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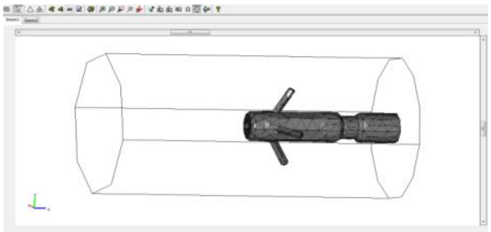

(c) Coarser
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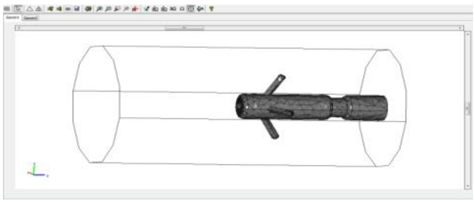

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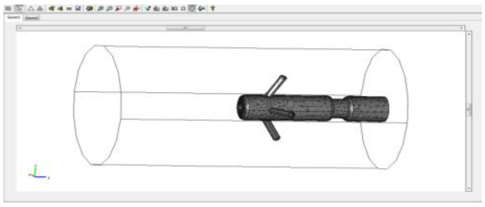
Degree of Freedom: 23232



(e) Normal
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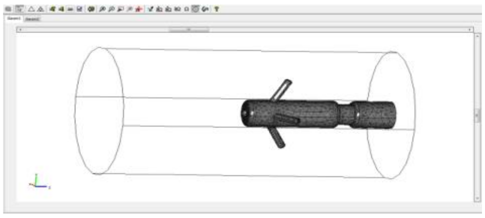

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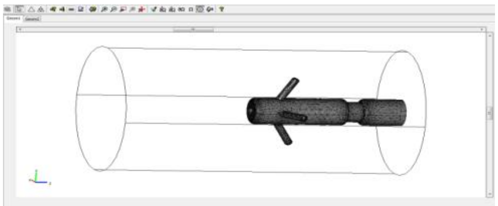

(g) Finer
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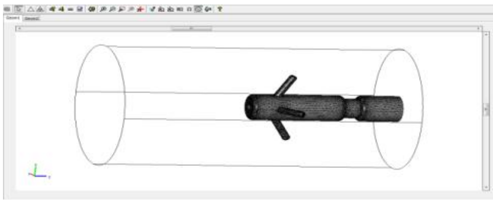
Degree of Freedom: 186108



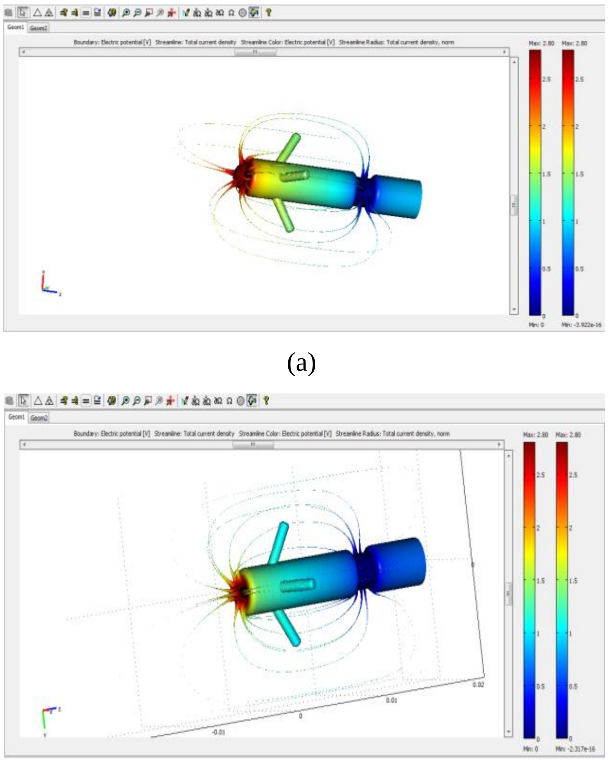
(h) Extra Fine
Number of elements: 274462
Degree of Freedom: 391703

Fig. 6 : Mesh plots of pacemaker electrode with radius equal to 0.5mm

It can be analysed from the figures that higher the number of elements, better is the accuracy in results. However, the computational time increases with increase in the number of elements, but this is not a significant limitation nowadays because of availability of the advance processors.

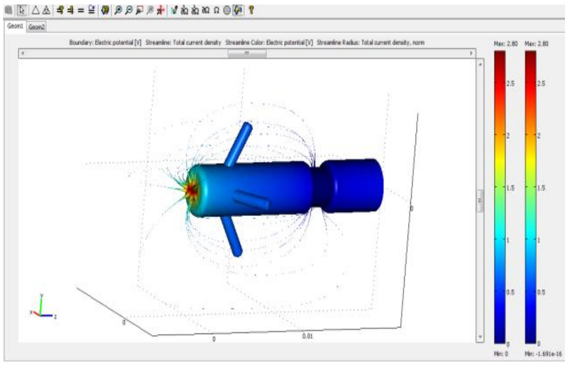
IV. RESULTS AND DISCUSSION

The simulation of pacemaker electrode gives the potential distribution on the surface of the electrode and the streamlines of the current distribution inside the human heart. The figure 7 shows the electrostatic potential distribution on the surface of the electrode and the total current density which is shown as streamlines for different tip sizes.



(a)

(b)



(c)

Fig.7 : Electrostatic potential on the surface of the electrode and current distribution shown as streamlines for different tip size with radius (a) 1.6mm (b) 1mm (c) 0.5mm

From the plots it can be made out that the current density is highest at the small hemisphere, which causes the excitation of the heart. It can also be seen that the current density is fairly uniform at the working electrode. Since the counter electrode is large therefore there are larger variations in current density on its surface. The model shows that the current is lower with the distance.

A correctly chosen radius of the tip of pacemaker electrode results in a tip size optimized for maximum electric field density at the myocardium. By decreasing the geometric size of the electrode tip the electric field density required to induce myocardial muscle contraction during pacing increases and there is efficient transfer of energy from electrode tip to heart. This is shown in figure 7(b). Whereas by increasing the geometric tip size disperses the electrode's induced electric field and thus decreases the efficacy of the electrode as shown in figure 7(a). This reduction in the electric field density causes decrease in the electrical influence on any one of the myocardial cells. Hence to reduce dispersion of the induced electric field, the tip's geometric size should be decreased. The optimal radius of the electrode tip is from 0.8mm to 1.4 mm [11].

Decreasing the size of the electrode tip below the optimal range, in order to increase the electric field density causes tissue trauma. This is as shown in figure 7(c). This also increases the sensing impedance of the electrode tip which is undesirable for the optimised performance of the electrode.

V. CONCLUSIONS

A 3D model of pacemaker electrode has been presented in this paper for maintaining normal rhythmic activity of heart. This work also performs the analysis of the potential distribution on the surface of the electrode and the current distribution inside the human heart for different electrode tip size.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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