FINITE ELEMENT MODELLING OF PACEMAKER ELECTRODE FOR TIME VARYING EXCITATION

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3D modelling; Pacemaker electrode; Finite element method; Time varying excitation

ABSTRACT

In an adult person, heart normally beats 60 to 100 times in resting state. But there are cases when the heart does not beat rhythmically. This may happen either due to blockage or slow electrical conduction system of the heart. Such conditions can be fatal and thus gives rise to the need of deploying an artificial pacemaker in the patient to maintain normal rhythmic activity of the heart. An artificial pacemaker delivers electrical impulses to the heart muscles via electrode which is also called pacemaker electrode. A three-dimensional computer simulation of a pacemaker electrode for time varying excitation, has been presented in this paper for modelling the voltage and current distributions in human heart using Finite Element Method.

INTRODUCTION

An artificial pacemaker is a medical device which is used to maintain normal rhythmic activity of the heart. It consists of a pulse generator and one or more leads. The pulse generator is an electronic device which is capable of generating electric pulses for stimulating the heart muscles as given in [1][2].

There are different techniques that can be used for the analysis of the pacemaker electrode. These are the analytical method, experimental method and the numerical method. The analytical method is used for simple geometries as shown in [3] whereas, the cost of setting up the laboratory equipment is high in case of experimental method, and also it is difficult to create complex physical phantoms [4]. Keeping in view these constrains, finite element method, which is one of the numerical methods, has been preferred increasingly [5]-[9]. Analysis of the optimal electrode placement, size and electrolyte resistivity using finite element method is given in [10]. A 2D finite element model to access the current density distribution in atrial pacing is shown in [11]. 3D modelling of a pacemaker electrode with different tip size showing the effect of tip radius on the voltage distribution on the surface of the electrode and current distribution inside the heart is shown in [12].

Finite element method (FEM) is known for its flexibility and versatility. FEM uses three steps for solving a problem: pre-processing, solution and post-processing. Pre-processing involves defining geometry, application of boundary conditions and mesh generation. In mesh generation, the complex geometry is broken into a number of small elements called finite elements that are governed by the finite element equations. The finite element equations are solved to obtain the solution. Post-processing enables visualisation of results and obtaining secondary quantities. In this paper 3D modelling of pacemaker electrode is done which is better than 2D modelling since it provides more realistic results.

This paper is organised in 5 sections. The following section gives the 3D geometrical design of the pacemaker electrode along with the description of the boundary conditions. The section after that gives the modelling and meshing of the pacemaker electrode. Proceeding that there is a section that gives the explanation of the results obtained and discussion, before the conclusion section.

3D GEOMETRICAL DESCRIPTION OF PACEMAKER ELECTRODE

The Fig. 1 shows an artificial pacemaker with a pulse generator and a pacemaker electrode. The leads connect the pulse generator to the heart muscles via electrodes. These electrodes deliver electrical pulses, generated by the pulse generator, to the heart muscles in order to regulate the beating of the heart.

The geometry of a pacemaker electrode consists of a supporting cylinder at the tip of which an active electrode is placed in form of a small hemisphere. Figure 2 shows a pacemaker electrode with its surrounding modelling domain. The counter electrode is placed at the waist of the supporting cylinder. Hence, a pacemaker electrode basically consists of two electrodes, tip acts as anode and the waist acts as cathode. The geometry of pacemaker electrode also has four thin cylindrical structures extending outwards. These thin cylinderical structures are called tines. Tines get entangled to the netlike lining of the heart called trabeculae and provides passive fixation [2]. The domain around the pacemaker electrode consists of blood and tissue. The do-

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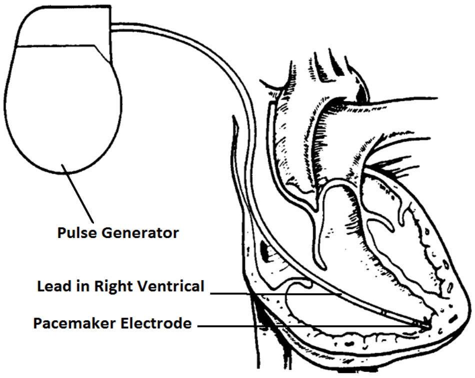

Fig. 1. Artificial pacemaker with pulse generator, lead and electrode.

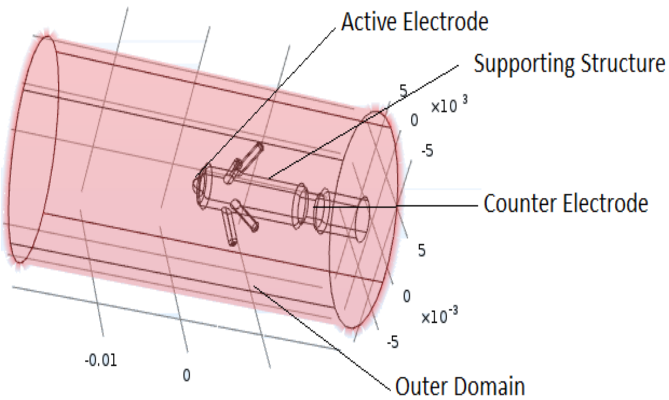

Fig. 2. Pacemaker electrode with surrounding domain.

main of the pacemaker electrode carries current which follows the Maxwell's equations

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

where, V is the voltage and σ is the conductivity of the human heart. The current density and the electric field are respectively given by the following two equations

$$J = (\sigma + \epsilon_o \epsilon_r \frac{\partial}{\partial t})E \tag{2}$$

$$E = -\bigtriangledown V \tag{3}$$

σ and ϵ_r are taken from the material of the heart. Conductivity, σ is taken to be $5000S/m$ and relative permittivity, ϵ_r is taken to be 1.

A time dependent study is performed on the pacemaker electrode. The excitation is applied to the active electrode and the counter electrode is grounded. The remaining part of the geometry is electrically insulated.

MODELLING AND MESHING

Comsol Multiphysics software is used to perform 3D modelling of the pacemaker electrode [22]. Figure 3 shows a 3D model of the pacemaker electrode. The tip of the electrode i.e. the active electrode is applied with a potential of 5V for duration of 0.6ms. This value

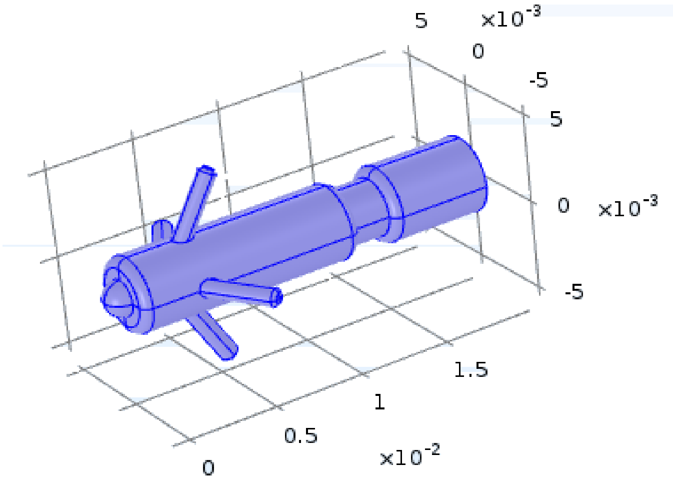

Fig. 3. 3D model of the pacemaker electrode.

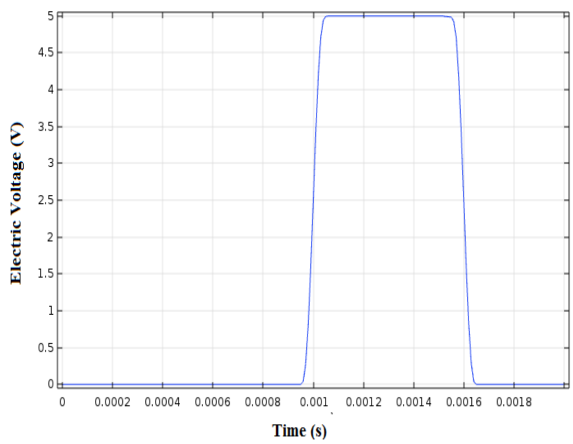

Fig. 4. Voltage pulse of duration 0.6ms applied to the electrode tip.

is chosen because modern pulse generators produce an output pulse of amplitude from 0.8 to 5V. The duration of this pulse is chosen in the interval 0.1 to 1.5ms as given in [13][14]. This pulse acts as input to the active electrode of the pacemaker. Figure 4 shows the voltage pulse applied to the active electrode. To the counter electrode which is placed at the thinner waist of the structure, ground potential is applied as boundary condition. The rest of the boundaries are electrically insulated which is given by the following equation

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

where n is the outward normal. The boundaries of the outer domain as shown in Fig. 2, are placed far enough from the electrode such that it gives a very small impact on the current and potential distribution.

Once the 3D model of the pacemaker is made and appropriate boundary conditions are applied, meshing is done with tetrahedral elements. Finite element modelling was carried out using different mesh sizes. Figure 5 shows the mesh plot of pacemaker electrode with 27865 nodes.

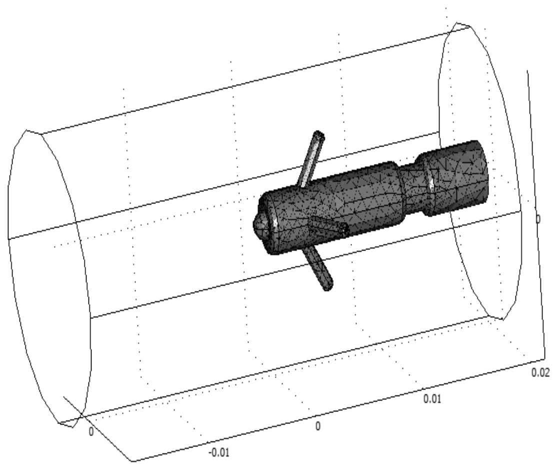

Fig. 5. Mesh plot of the pacemaker electrode with 27865 nodes.

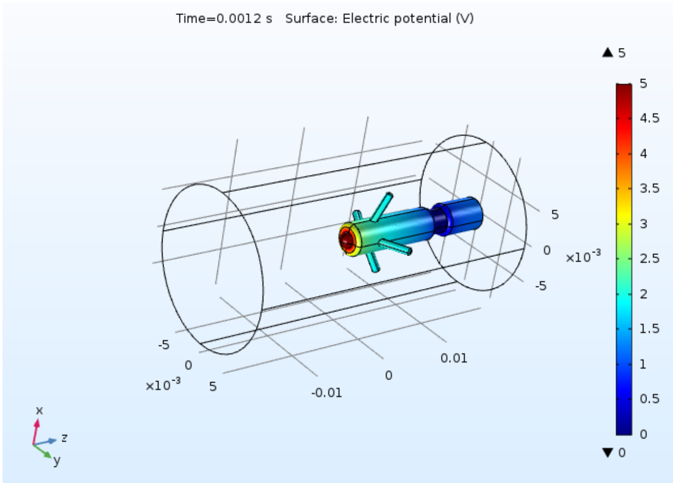

Fig. 6. Surface plot showing electric potential (V) at Time=0.0012s.

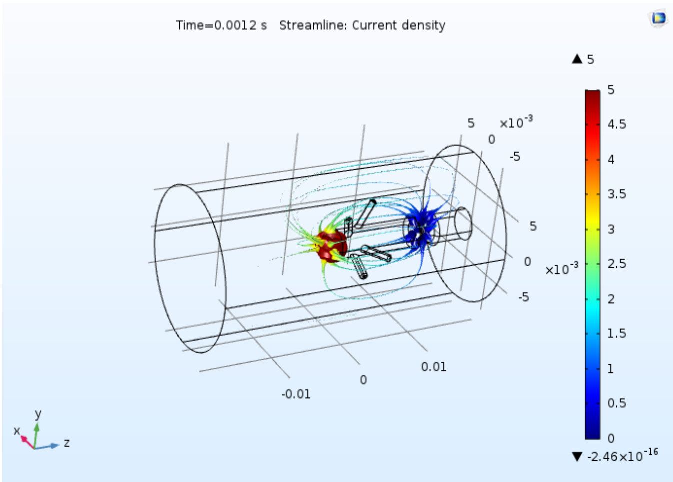

Fig. 7. Streamline plot showing current density at Time=0.0012s.

RESULTS

3D simulation of pacemaker electrode gives voltage distribution at the surface of the electrode and the current distribution inside the heart. Figure 6 shows the potential distribution on the surface of the electrode and Fig. 7 shows the total current density by the streamlines around the pacemaker electrode. These plots have been shown at time 0.0012s, which is a representative point in time during the interval of the input pulse, as shown in Fig. 4. From Fig. 7, it can be seen that the current density is highest at the active electrode. This causes the excitation of the heart. Also, the current density is uniform at the active electrode. The counter electrode is large and therefore there is larger variation in the current density on its surface.

The middle layer of the heart muscle is called myocardium and it is responsible for conduction of electric impulses. Therefore, for optimized performance of the pacemaker electrode, the radius of the active electrode should be chosen such that there is maximum current density at the myocardium of the heart [12]. Too much increasing of the tip size would decrease the electric influence on the heart cells whereas, decreasing it too much would cause localised tissue traumas. The optimal radius of the electrode tip is from 0.8mm to 1.4mm as given in [15]. The tip radius of the pacemaker electrode is chosen to be 1mm in this paper.

Figure 8 shows few representative points numbering, 1, 2, 3, 4, and 5, at different locations on the surface of the pacemaker electrode geometry. Figure 9 shows the time history plots of these selected points. This plot resembles the voltage pulse plot that is fed to the tip of the electrode. This plot also gives a view of how voltage magnitude changes over the surface of the pacemaker electrode.

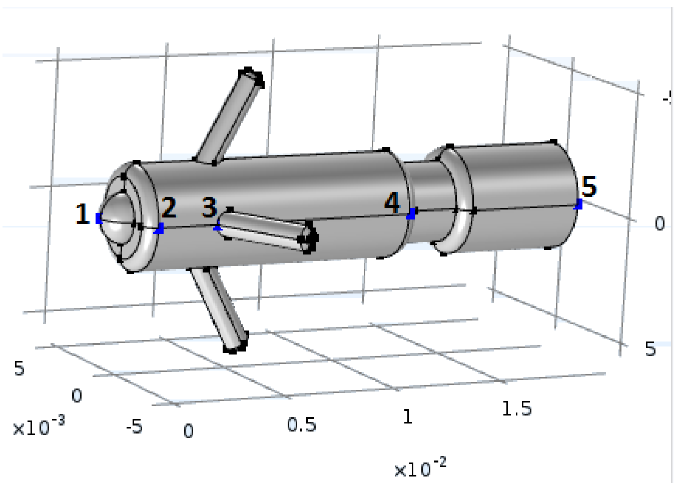

Fig. 8. Selected points on the surface of pacemaker electrode.

Discussion

Three-dimensional cardiac and implantable pacemaker modelling is getting popular and many researchers are adopting this technique to do various analysis such as understanding electrophysiology of the

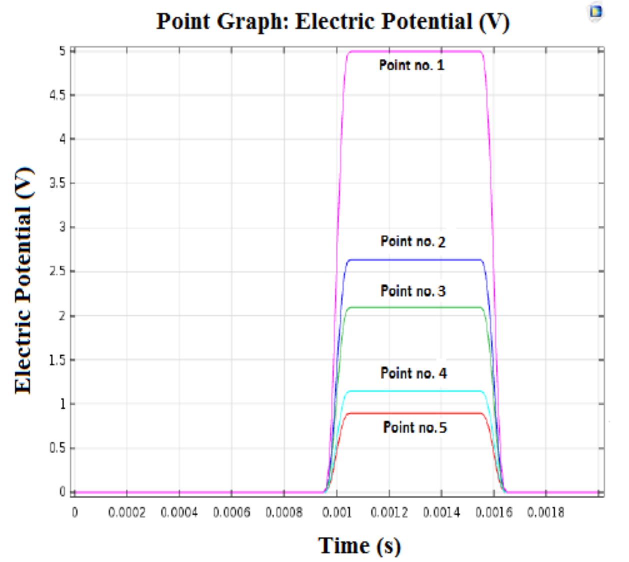

Fig. 9. Time history plot of few selected points on the geometry.

heart, complex cardiac diseases, patient specific excitations for the heart etc. [16]. The importance of developing virtual 3D heart models for understanding the structural complexity of paediatric hearts is given in [17]. It shows how the models of the human thorax can be used to predict the defibrillator's electric field intensity and the amount of current to reach the human heart. Thorough analysis and verification of a dual chamber pacemaker has been performed in [18]. It verified a dual chamber pacemaker model against a set of safety properties. In [19] a novel hybrid heart model was developed in Simulink that worked directly with the action potential signal from specific cardiac cells and was suitable for quantitive verification of implantable cardiac pacemakers. A model based framework was developed that supported quantitative verification of implantable cardiac pacemakers over hybrid heart models [20]. Use of genetic algorithms for improving pacemaker efficiency of defective heart was shown in [21].

Though, lot of work has been done on the simulation and analysis of various heart models, it is hard to find the modelling and analysis of artificial pacemakers, especially the pacemaker electrode which is actually responsible for transmitting the electrical impulses to the heart tissue. The simulation results of pacemaker electrode in this paper demonstrates the voltage and current distributions in heart. The electrode tip radius is chosen such that it produces optimum electric field distribution in the heart tissue. The consequences of choosing any pacemaker electrode tip radius have been discussed in [12].

CONCLUSIONS

Artificial pacemakers are used to regulate the heart rate by stimulating the heart cells and causing the contraction of the heart muscles. For time varying excitation, this paper gives a 3D finite element simulation of the pacemaker electrode using COMSOL Multiphysics software. In particular, it gives the potential distribution on the surface of the electrode and the current distribution inside the human heart. The voltage and current distributions are shown in the plots.

References

[1] Christoffels VM, Moorman AFM. 2009. Development of the cardiac conduction system: why are some regions of the heart more arrhythmogenic than others? Circulation: Arrhythmia and electrophysiology. 2:195–207.

[2] Stokes K. 1990. Implantable pacing lead technology. Engineering in Medicine and Biology Magazine, IEEE. 9:43–49.

[3] Gaffour L. 1998. Analytical method for solving the one dimensional wave equation with moving boundary. Journal of Electromagnetic Waves and Applications. 20(11):1429–1430.

[4] Ibrahim WMA, Algobroum HM, Almaqtari MT. 2008. Short review on the used recipies to simulate the bio-tissue at microwave frequencies. Proceedings of 4^{th} Kuala Lumpur International Conference on Biomedical Engineering; June 25–28; Kuala Lumpur, Malaysia. 21:234–237.

[5] Rao SS. 2005. The finite element method in engineering. Elsevier Butterworth-Heinemann, 4^{th} edition.

[6] Ciarlet PG, Lions JL. (1995). Handbook of numerical analysis: finite element methods (Part 2), numerical methods for solids (Part 2). North Holland. 4.

[7] Reddy J. 2005. An introduction to finite element method, 3^{rd} edition. McGraw-Hill Education.

[8] Chandrupatla TR. 2004. Finite element analysis. Engineering and Technology.

[9] Kolston PJ. 2000. Finite elememt modelling: a new tool for the biologist. Philosophical Transaction of the Royal Society A. 358:611–631.

[10] Panescu D, Webster JG, Tompkins WJ, Stratucker RA. 1995. Optimising of transcutaneous cardiac pacing by three dimensional finite element modelling of the human thorax. Medical and Biological Engineering and Computing. 33:769–775.

[11] Krasteva V. 2003. Finite element modelling approach for optimal electrode configuration in atrial pacing. Computers in Cardiology. 30:441–444.

[12] Kalra S, Marwaha S. 2013. Design and optimisation of pacemaker electrode using finite element method. International Journal of Advanced Electrical and Electronics Engineering, 2(6):125–130.

[13] Forde M, Ridgely P. 2000. Implantable cardiac pacemakers. The Biomedical Engineering Handbook: 2^{nd} Edition.

[14] Sanders RS. 2008. The pulse generator. Cardiac Pacing for the Clinician. 47–71.

[15] Wagner BK. 1995. Design of Cardiac Pacemaker. IEEE. 12:132–160.

[16] Lopez-Perez A, Sebastian R, Ferrero JM. 2015. Three-dimensional cardiac computational modelling: methods, features and applications. BioMedical Engineering Online, 14(35):1–31.

[17] Trayanova NA. 2014. Virtual 3D heart models to aid pacemaker implantation in children. Future Cardiol, 10(1):5–8.

[18] Jiang Z, Pajic M, Moarref S, Alur R, Mangharam R. 2012. Modeling and verification of a dual chamber implantable pacemaker. International Conference on Tools and Algorithms for the Construction and Analysis of Systems, March 24–april 1; Tallinn, Estonia. 4(16):188-203.

[19] Chen T, Diciolla M, Kwiatkowska M, Mereacre A. 2013. A simulink hybrid heart model for quantitative verification of cardiac pacemakers. HSCC'13, April 8–11, Philadelphia, Pennsylvania, USA. 131–136.

[20] Chen T, Diciolla M, Kwiatkowska M, Mereacre A. 2014. Quantitative verification of implantable cardiac pacemakers over hybrid heart models. Information and Computation, 236:87–101.

[21] Dumas L, Alaoui L. 2007. How genetic algorithms can improve a pacemaker efficiency. GECCO'07, July 7–11; London, England, United Kingdom, 2681–2685.

[22] Comsol Multiphysics User Guide. Available from: https//:www.comsol.co.in

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