Modeling and simulation of cardio electrical activity for ischemia using comsol multiphysics tool

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Abstract

The circulatory system revolves around the heart, which is of blood vessels network that transports blood to all part of the body. All organs of human rely on blood for transport of oxygen and some other vital nutrients, ensuring that they remain good healthy and properly function. The heart is very important for blood pumping throughout the circulatory system. When the supply of blood to tissues is restricted, oxygen lack for cellular metabolism occurs (to keep tissue alive). Ischemia is a vascular disease in which arterial blood flow is interrupted to a tissue, organ, or extremity, resulting in tissue death if left untreated. It can be caused by embolism, atherosclerotic artery thrombosis, or trauma. Acute arterial ischemia can be caused by venous issues such as venous outflow blockage and low-flow conditions. One of the most common causes of acute arterial ischemia is an aneurysm. The importance of the heart structure on COMSOL Multiphysics is highlighted as it can be modeled and simulated for cardiac contraction and relaxation. The heart cavity structure is implemented using the FHN (Fitzhugh Nagumo equation) and LG (Landau Ginzberg equation) equations along with the corner cases in this paper. The model of the heart is divided into 4 different models to demonstrate the blood flow. The changes for the 4 models are in terms of mesh and the cavity change of heart structure which indirectly demonstrates the blood movement of the heart. The observed plots are in terms of spiral waves and also the waves for the dependent variables are plotted.

1. Introduction

To understand the heart dilation and contraction pattern requires modeling electrical activity in cardiac tissue. The sinus node is a location on the heart that produces rhythmic electrical pulses. The electrical pulses, in turn, cause the muscle to contract mechanically. In a normal heart, damping of electrical pulses occurs, but numerous cardiac illnesses increase the likelihood of signals re-entering. This indicates that the typical steady pulse has been disrupted, a serious and urgent disorder known as arrhythmia. In this paper, Complex Ginzburg-Landau equations and Fitzhugh-Nagumo equations, both are solved on the identical geometry, are used to investigate various propagation aspects of electrical signal in heart tissue. The examination by E J Benjamin et al., at the Statistical Update presents the updated information on a scope of clinical heart and circulatory sickness conditions (counting stroke, inherent coronary illness, musicality problems, subclinical atherosclerosis, coronary illness, cardiovascular breakdown, valvular infection, venous illness, and fringe vein illness) and the related results (counting nature of care, methods, and monetary expenses) [1]. N Biasi et al., in their work proposed a shut circle model of cardiovascular incitement utilizing a limited component model of entire heart installed in middle that is suggested as a valuable device for testing and pacemaker plan [2].

M Boulakia et al., in their study manages the mathematical re-enactment of electrocardiograms (ECG) [3]. The M Boulakia in their work mentioned that the point is to devise a numerical model for given incomplete differential conditions, which can give reasonable 12-lead ECGs [4]. The C S Henriquez et al., in their paper proposes the displaying of the cardiovascular framework involves dealing with a variety of wonders relating to different time, constitutive, and mathematical scales [5]. The proposed approach by
Cha´vez CE et al., is the backward issue of electrocardiography (IPE) has been detailed in various routes to non-obtrusively get significant data about the heart condition [6]. Model conditions were tried utilizing an improvement on math containing major topological highlights of the two atria. M Janse created a model which can unconstraint enactment of electrical motivations inside the sinoatrial hub which spread across the atria [7].

The model can be utilized as a reason for examining systems hidden typical and unusual atrial rhythms, remembering re-contestant enactment by an ectopic concentration was proposed by Dokos S et al., [8]. The Ferrero J et al., in their paper used personal computer for demonstrating to research the components in figure-of-eight re-emergence during the intense stage or local myocardial ischemia [9]. An appropriately picked projection from the 4-dimensional HH stage space onto a plane creates a comparable graph which shows the fundamental connection between the two models has been proposed by Richard FitzHugh in their work [10]. D Gabor et al., Geselowitz has proposed that forward issue of electrocardiography alludes to the estimation of the possibilities on the body surface because of the heat sources, utilizing the hypothetical conditions of electromagnetism [11, 12].

The A M Janssen et al., demonstrates that the complex microstructure of heart muscle contained coupled cells, wrapped by an interstitial comprised of veins, connective tissue, and liquid presents some undeniable issues to those keen on understanding the tissue as an electrical medium [13]. Zhihao Jiang et al., proposed Bidomain Model is utilized to process the spatial dissemination of the electrical potential [14]. The incomplete differential conditions are discretized with the limited component strategy and the multigrid technique is utilized to tackle the comparing direct conditions were demonstrated by Joseph Lau et al., [15]. G T Lines et al., in their work have proposed the usage of designing science and innovation to natural cells and tissues that are electrically directing and edgy [16]. Potse depicted the hypothesis and a wide scope of utilization in both electric and attractive fields in their work [17].

C H Luo et al., in their paper shown an extraordinary computerized bandpass channel decreases bogus identifications brought about by the different sorts of impedance present in ECG signals [18]. Pinto et al., proposes that similitudes and contrasts among bioelectricity and biomagnetism are depicted exhaustively from the perspective of the lead field hypothesis [19]. The inference drawn from the above literature review is that the heart simulation is done for specific changes using few tools and there is a gap in working on the blood flow movement happening in the heart. This is demonstrated in this work. Simulation of heart's electrical activity for bio-medical application using COMSOL Multiphysics.

2. Methodology

COMSOL tool is used to observe the heart electrical activity. The behavior of heart during different situations like stress, happiness, and high blood pressure, etc. analyzed using COMSOL Multiphysics. The contraction and relaxation of the heart by the blood flow are analyzed by the movement of the heart cavity on the tool by defined models. In the COMSOL the values is analyzed by the change done on the cavity and change in the mesh dimensions.
The ischemia is caused due to abnormal movement of blood in heart arteries. This phenomenon can be used and can be duplicated on the COMSOL tool. This process is done on the tool by having variation in the inner cavity of heart indirectly representing the abnormalities on heart from ischemia [20].

The methodology for the work is to meet the defined objective is implemented through the Fig. 1. The basic flow is primarily to understand the functioning of the heart and its relation to mathematical modelling for implementing on COMSOL Multiphysics. The understanding of the equation for the processing of the data and the constraints to be implemented is done as shown in Fig. 1. In the methodology flow, the primary thing is to study the behaviour of heart to different pressure and feels [21]. Once the study on heart is done later on, the understanding of the equation is necessary and their implementation on COMSOL is a must. The final modelled and simulated diagrams of heart and their behaviour for the applied inputs.

In the next section, the basic modelling of heart with cavities and different mesh style will be explored to check the impact on the heart for different time changes to see the impact of ischemia [22].

3. Implementation On Comsol For Unique Cardio Models

The methodology implemented to perform the desired objective is discussed in this section. To implement the heart movement on COMSOL the Fitzhugh-Nagumo equations and Complex Landau-Ginzburg Equations is used.

a. Fitzhugh-Nagumo equations

Fitzhugh – Nagumo equations are the primary equations that may be used to model the heart, together with COMSOL, to observe the behavior and check the influence of standard equations and their reaction to the given stimulus.

\[
\frac{\partial u_1}{\partial t} = \Delta u + (\alpha - u_1) (u_1 - 1) u_1 + (-u_2) (1)
\]

\[
\frac{\partial u_2}{\partial t} = \varepsilon (\beta u_1 - \gamma u_2) (2)
\]

An action potential is represented by the variable of activator \( u_1 \), and a variable of gate is represented by the gate variable \( u_2 \) [23]. The insulating boundary conditions for \( u_1 \) assume that no current flows into or out of the heart. The corner cases, from (1) & (2)

\[
u_1 (0,x,y,z) = v_0 ((x + d) > 0) ((z + d) > 0),
\]

\[
u_2 (0,x,y,z) = v_2 ((-x + d) > 0) ((z + d) > 0).
\]

The condition initially defines an \( u_1 \) initial potential, where one of the heart quadrants is at constant, however remaining been at rest, the \( v_0 \) is elevated potential. The values ‘\( x \)’ and ‘\( d \)’ for the changes should be less than 0 for dependent variable \( v_0 \).
Similarly, v2 must keep the value of (-x + d) <‘0’. To satisfy the equation, the value (z + d) must be greater than zero. The following logical expressions can be used to implement this initial distribution, where TRUE equals 1 and FALSE equals 0. Here, d equals $10^{-5}$, which is used in the formulas for raising the raised slightly potential over the major axes.

b. The Complex Landau-Ginzburg Equations

$$ \frac{\delta v_1}{\delta t} - \Delta (v_1 - c_1v_2) = v_1 - (v_1 - c_3v_2)(v_1^2 - v_2^2) \quad (3) $$

The activator and inhibitor (3) variables are $v_1$ and $v_2$, respectively. Constants $c_3$ and $c_1$ are parameters that reflect the material's properties. Existence and nature of stable solutions are also determined by these constants. The following are the initial conditions that result in a smooth transition step near $z = 0$:

- $v_1(0, x, y, z) = \tanh(z)$
- $v_2(0, x, y, z) = -\tanh(z)$.

c. Parameters

The parameter used to define equations 1, 2, and 3 are expressed in Table 1. The Table 1 shown here accepts various values for the simulation of the heart. The values for alpha, beta, epsilon, gamma, delta, $V_0$, $\nu_0$, d, $c_1$, and $c_3$ constants used are pre-defined using Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>epsilon</td>
<td>0.01</td>
<td>excitability</td>
</tr>
<tr>
<td>gamma</td>
<td>1</td>
<td>system's parameter</td>
</tr>
<tr>
<td>alpha</td>
<td>0.1</td>
<td>excitation threshold</td>
</tr>
<tr>
<td>beta</td>
<td>0.5</td>
<td>system's parameter</td>
</tr>
<tr>
<td>$\nu_0$</td>
<td>0.3</td>
<td>inhibitor value elevated</td>
</tr>
<tr>
<td>delta</td>
<td>0</td>
<td>system's parameter</td>
</tr>
<tr>
<td>$V_0$</td>
<td>1</td>
<td>potential value elevated</td>
</tr>
<tr>
<td>d</td>
<td>1E - 5</td>
<td>shift distance off-axis</td>
</tr>
<tr>
<td>$c_3$</td>
<td>-0.2</td>
<td>PDE parameter</td>
</tr>
<tr>
<td>$c_1$</td>
<td>2</td>
<td>PDE parameter</td>
</tr>
</tbody>
</table>

The values for alpha, gamma, beta, and delta are used to implement in the equations (1) & (2) for modeling of heart structure on the simulation tool. The constants $c_1$ and $c_3$ have 2 and −0.2 values for
the PDE parameter as shown in Table 1. The values such as less element quality, average quality of element, triangle, tetrahedron, element edge, and element vertex used for implementation are shown in Table 2 for various models that are used to analyze heart on the COMSOL tool.

d. Models

The different models are designed to have better results to compare on the heart simulations modeled from the equation. The model 1 and model 4 has the same mesh value but different cavity as signifying the expansion of heart tubes due to ischemia. Similarly, model 2 and model 3 have the same mesh value but the different cavity in them. These models are important to analyze on different aspects which will be discussed in the section [24].

The minimum element quality is in the range of 0–1 that is because it considers the values in terms of percentage and their value for all the models is almost equal to ~ 2.5. Similarly, the average element quality for the 4 models is ~ 0.7. The edge value for model 1 to model 4 is arranged in decreasing order [25]. In Fig. 2, the mesh analysis is shown for various models i.e., models 1, 2, 3 & 4. This is modeled using Table 1 and Table 2.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value(Model 1)</th>
<th>Value(Model 2)</th>
<th>Value(Model 3)</th>
<th>Value(Model 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum element quality</td>
<td>0.2592</td>
<td>0.2346</td>
<td>0.2518</td>
<td>0.2715</td>
</tr>
<tr>
<td>Average element quality</td>
<td>0.709</td>
<td>0.7065</td>
<td>0.6863</td>
<td>0.7186</td>
</tr>
<tr>
<td>Tetrahedron</td>
<td>28498</td>
<td>28621</td>
<td>17127</td>
<td>4572</td>
</tr>
<tr>
<td>Triangle</td>
<td>3802</td>
<td>4074</td>
<td>2762</td>
<td>1188</td>
</tr>
<tr>
<td>Edge element</td>
<td>306</td>
<td>336</td>
<td>276</td>
<td>164</td>
</tr>
<tr>
<td>Vertex element</td>
<td>16</td>
<td>23</td>
<td>23</td>
<td>16</td>
</tr>
</tbody>
</table>

4. Results And Discussion

The implementation of the heart is performed on COMSOL to observe the variations reproduced on heart models. In this section, the final results obtained after simulating the heart on the tool and comparison of the different models are done.

a. Models – spiral waves

- Model 1:
Figure 3 gives the clear picture of the simulated view of heart at different dependent variable used in the equation 1 and 2. The variation observed in figure 3 (a) is the surface view of the heart for model 1 for dependent variable u1 at time t=500s. for the same model, the cavity view at t=120s is shown in figure 3 (b). After using the LG equation, it is observed for 2 more plots, the figure 3 (c) shows the view of heart interior changes at time t=75s. The spiral view of model 1 at time t=45s is shown in figure 3 (d) formed from the LG equation.

• Model 2:

Model 2 contains the changes done to the heart based on the mesh and the cavity observation for the movement of blood. Figure 4 shows the simulated view of the heart on COMSOL for model 2. The dependent variable u1 from the FN equation for the surface is shown in figure 4 (a) and the cavity view in figure 4 (b) for observations. As the simulation became more critical, the shift to the LG equation is shown in figure 4 (c) for dependent variable v1 at time t=75s. the final surface view for model 2 is shown in figure 4 (d) at time t=45s.

• Model 3:

In this section, model 3 shows the simulated view of the heart defined for the different cavity than the other models but the mesh analysis is relative to model 2. The COMSOL tool has simulated the defined model to produce the spiral wave as shown in figure 5 for FN and LG equation. The variation of heart for the cavity and mesh changes done in model 3 is shown in figure 5. In figure 5 (a) the interior cavity of the heart is shown at time t=500s for the dependent variable u1. For the same variable, the surface view is shown at t=120s in figure 5 (b). Similarly, after applying the LG equations and providing the boundary conditions in COMSOL it can be observed in figure 5 (c) for variable v1 at t=75s. Also, in figure 5 (d) the complete spiral view is shown for model 3.

• Model 4:

Model 4 has a cavity change concerning model 1 but the mesh changes have been similar to that of model 1. This section shows the simulated view for the heart on COMSOL for analysis and their reaction to the differential equation and their behavior to the applied stimulus. In figure 6 (a) the dependent variable u1 for model 4 at time t=500s. the same model for the cavity change is shown in figure 6 (b) at time t=120s. In figure 6 (c) the heart is simulated after applying the LG equation for dependent variable v1. Also, for the same variable, the surface spiral wave is shown in figure 6 (d).

b. Analysis of values

In this section, the complete analysis of the dependent variables on the simulated heart is discussed. The various waveforms related to time and its dependence on the arc length of the heart is shown in the following waveforms in this section.
Figure 7 depicts the behavior of the heart from the arc length from 10 for the dependent variable $u_2$. The value of $u_2$ changes from -0.04 to a maximum value of 0.32 in the small range of arc length for $10 \pm 5$. The whole dimension change happens at time $t=75s$. The sudden increase of variable $u_2$ at an arc length of 10 happens and remains constant as shown in figure 7. Similarly, in figure 8 the dependent variable $u_2$ along the x-direction is varied along the arc length for the time $t=75s$. Figure 12 shows the variation close to the arc length of 10 the sudden change happens to the gradient of $u_2$, the value shoots up to 0.06. So, the main observation here is the change that has to be done at an arc length of 10.

In figure 9, the values corresponding to the LG equation for the dependent variable $v_1$ along the different time lines from 0s to 75s. The value can be observed for $t=70s$ the variation of $v_1$ is from -1 to max value and also at different time frames the arc length of the 30s reaches the high state value as shown in figure 9. The waves look chaotic but the waves at an arc length of 30 give the best view for all the desired timelines. In figure 10, the variable $v_1$, first-time derivative $v/s$ arc length along the time change is shown. Where the change in the value occurs at the period of 70s and the arc length of 10. Also, observing other timelines are almost has 0 value for $v_1$. In the LG equation, the derivative is used hence the plot depicts its value.

The variable used in the LG equation to change the cavity in the heart using COMSOL is an important factor as that will have an overall impact on the design simulation. Figure 11 shows the variable $v_1$, x component $v/s$ arc length along with the time change as during the time $t=35s$ the value happens to change from -0.6 to +2 for the range in between the arc length of 10. In figure 12, the variation of dependent variable $v_2$ along different time frames happens. The variable $v_2$ changes it value from -1 to +1. The maximum value change happens at the arc length of 40. Most of the time frames are high at the arc length of 40.

For Ischemia the complete contraction and relaxation of blood flow in the heart is depicted in 4 models and analyzed using waves. The results of the obtained simulated heart have been discussed in this chapter along with the desired waves related to the dependent variables $v_1$ and $v_2$ used in the equation (1) & (3).

**Conclusion And Future Scope**

Complete simulation of the heart for the change in the cavity has been done on the COMSOL tool. The values are also measured and implemented for observation in the tool. The model has the value of maximum +2 for the change in arc length of 10 for the variable $u_2$. Similarly, for variable $v_1$ the change in the arc length can be observed to the maximum at 30. This approach of analyzing the heart on the tool for human issues like ischemia will be the future of modern medicine. Also, this approach helps the doctor to find the problem at a very early stage and soon the solution can also be framed by simulating using the required equations and formulating the constraints or the boundary values to the equation.

**Declarations**
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Ethical Approval**: Not Applicable

**Competing interests**: Not Applicable

**Authors' contributions**:

**Javalkar Vinay Kumar**: Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing

**N Shylashree**: Supervision, Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing

**Yatish D Vahvale**: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing

**V Sridhar**: Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Project administration, Writing – review & editing

**Manjunatha C**: Supervision, Conceptualization, Methodology, Writing – original draft, Project administration, Writing – review & editing

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**Availability of data and materials**: Not Applicable

**References**


Figures
Figure 1

Shows the flow for the project
Figure 2

(a) mesh view of model 1, (b) mesh view of model 2, (c) mesh view of model 3, (d) mesh view of model 4.
Figure 3

(a) variation of heart interior for FN equation at time=500s for u1, (b) variation of heart surface for FN equation at time=120s, (c) Spiral view of heart interior for variable v1 at time=75s using LG equation, (d) spiral view of heart surface for variable v1 at time=45s using LG equation.
Figure 4

(a) variation of heart interior for FN equation at time=500s for u1, (b) variation of heart surface for FN equation at time=120s, (c) Spiral view of heart interior for variable v1 at time=75s using LG equation, (d) spiral view of heart surface for variable v1 at time=45s using LG equation.
Figure 5

(a) variation of heart interior for FN equation at time=500s for u1, (b) variation of heart surface for FN equation at time=120s, (c) Spiral view of heart interior for variable v1 at time=75s using LG equation, (d) spiral view of heart surface for variable v1 at time=45s using LG equation.
Figure 6

(a) variation of heart interior for FN equation at time=500s for u1, (b) variation of heart surface for FN equation at time=120s, (c) Spiral view of heart interior for variable v1 at time=75s using LG equation, (d) spiral view of heart surface for variable v1 at time=45s using LG equation.
Figure 7

variable $u_2$ v/s arc length along with the time change,

Figure 8
variable $u_2$, x component v/s arc length along with the time change

Figure 9

variable $v_1$ v/s arc length along with the time change,
Figure 10

variable v1, first-time derivative v/s arc length along with time change

Figure 11
variable v1, x component v/s arc length along with the time change,

Figure 12

variable V2 v/s arc length along with the time change