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Communication

The Heart Excitation Simulation Utility (HE-SU)

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Abstract

Accurate modeling of cardiac excitation propagation requires detailed representation of both the myocardial structure and the ventricular conduction system. Traditional imaging methods like MRI and CT provide anatomical data but fail to capture the anisotropic properties essential for realistic simulations. This work presents an integrated modeling and simulation environment, HE-SU (Heart Excitation Simulation Utility), which employs pre-processed Diffusion Tensor Imaging (DTI) data to reconstruct myocardial fiber architecture and conduction pathways. The simulation is based on the Monodomain reaction-diffusion equation using the Aliev-Panfilov adaptation of the FitzHugh-Nagumo model. The software enables the adjustment of conductivity parameters and visualizes the propagation of excitation in 3D, supporting exportable reports for further analysis. This tool is valuable for researchers studying cardiac electrophysiology and the impact of anisotropic tissue properties on body surface potential mapping (BSPM).

Keywords cardiac excitation modeling; diffusion tensor imaging (DTI); monodomain equation; myocardial fibers; conduction system; Aliev-Panfilov model; cardiac electrophysiology

1. Introduction

The myocardial and the conduction system are the two main structures that need to be taken into account while simulating the excitation propagation in the heart. MRIs and CT scans are two common medical imaging methods used to determine the anatomical structure of the heart. However, tissue anisotropy, which is essential for precise modeling, cannot be captured by these traditional imaging modalities. The myocardium has strong anisotropic properties that have a major impact on the heart's electrical and mechanical operations. Although some models assume the heart as an isotropic material [1–4], most acknowledge that it is anisotropic because anisotropy has a significant impact on the Body Surface Potential Map (BSPM) simulation results.

Determining the myocardial fiber architecture is crucial in anisotropic heart models and can be done in a number of ways. The work of Streeter et al. [5] is an example of a popular technique that uses dissection-based data to assign fiber orientations to each voxel in the anatomical heart model [6,7]. On the other hand, models such as Nielson et al. [8] specify fiber directions using mathematical formulations [9]. In more recent advances, fiber architectures are mapped using Diffusion Tensor Imaging (DTI). While DTI data is used in some models to solve the Forward and Inverse Problems [10,11], DTI is used mainly for geometric reconstruction in other models [12,13].

Before modeling, there may be some pre-processing that involves removing the heart from the surrounding tissues, such as blood vessels and adipose tissues. In order to ensure that the majority of the heart tissue is included in the model, it may be necessary to improve the masking pictures [14] before using clustering methods or manual segmentation.

The models outlined by Tawara [15], Massing et al. [16], and Durrer et al. [17] are the most widely used to identify the ventricular conduction system. Ventricular conduction systems are modeled by either constructing a network based on anatomical structure and activation isochrones [18–20] or assigning the early activation sites based on Durrer et al. data [21].

2. Methods

The excitation propagation of the heart is modeled based on the Monodomain reaction-diffusion equation in its normalized form namely [22]:

$$\frac{\partial u}{\partial t} = \nabla \cdot (D \nabla u) + f + g \quad (1)$$

where u and t represent the normalized transmembrane potential and the normalized time respectively, D is the normalized effective conductivity tensor of the heart material, f is the function that represent the reaction term due to ions exchange, and finally g represents the external applied input.

The electrical stimulation of the heart is modeled at the cellular level or for the entire tissue. FitzHugh and Nagumo's (FHN) most popular model for heart excitation [23] depicts the excitation by two variables that stand for the cell membrane's depolarization and repolarization. Aliev and Panfilov [24] updated the normalized form of the FHN model to incorporate the effect of Action Potential Duration (APD), however this model is simplified and provided in several forms [25,26].

$$f = -ku(u - a)(u - 1) - uv \quad (2)$$

such that

$$\frac{\partial v}{\partial t} = \varepsilon(u, v)(-v - ku(u - a - 1)) \quad (3)$$

and

$$\varepsilon(u, v) = \varepsilon_0 + \frac{\mu_1 v}{u + \mu_2} \quad (4)$$

where for the heart tissues, $k=8$, $a=0.15$, $\varepsilon_0=0.002$, $\mu_1=0.2$ and $\mu_2=0.3$.

3. Software Description

3.1. Main Form Interface

Figure 1 depicts the HE-SU's primary form. A pre-processed DTI heart model [27] with an extracted conduction network can be loaded by the user. The PMN file contains a heart that has been resized using the Moving Weighted Effective Sphere (MWES) Filter [28] from 256x256x110 to 55x55x55. The left branch bundle is represented by the red voxels, the right branch bundle by the blue voxels, and the myocardium by the gray voxels.

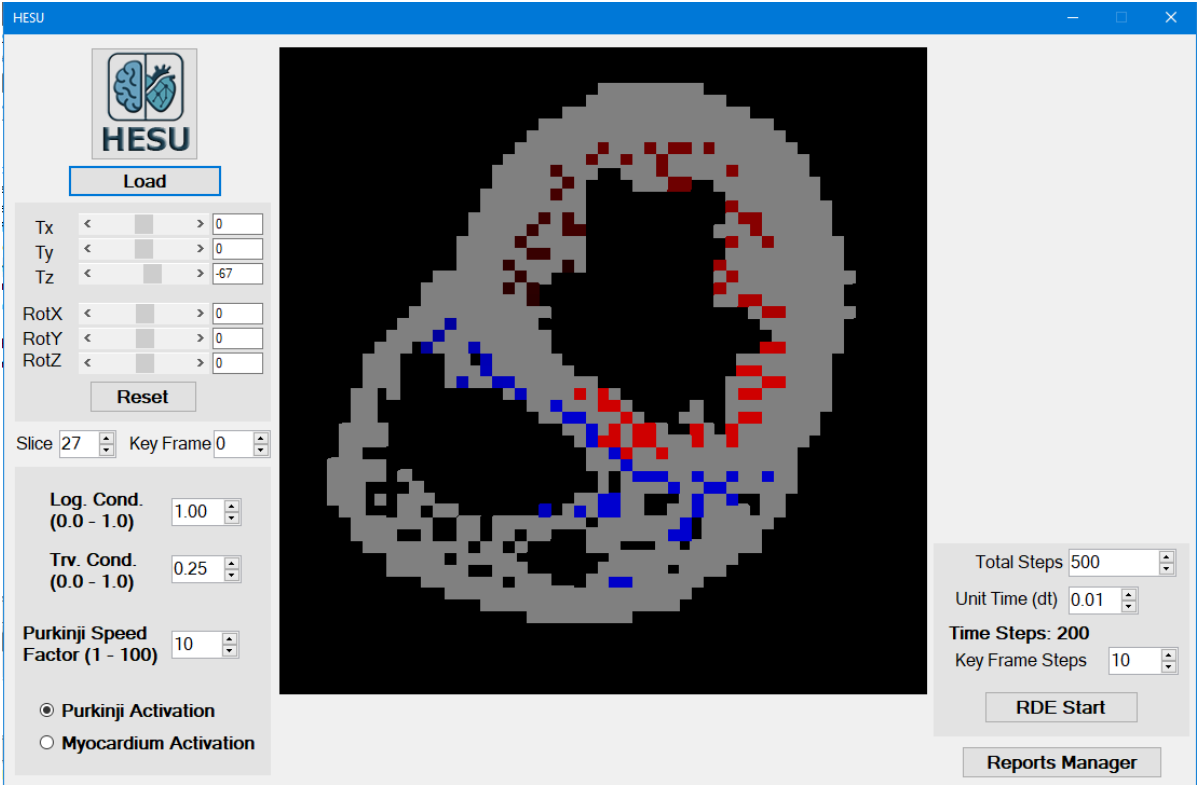


Figure 1. Main Form of HE-SU application showing the original image view.

In addition to the speed factor of the propagation of excitation in the conduction network in the longitudinal direction relative to the myocardial, the user can set the normalized conductivity of the myocardium in both longitudinal and transverse directions (the defaults are 1 and 0.25, respectively). Based on information from the literature, the ventricles' stated activation point, or His-Bundle, is set up for this heart.

After choosing the parameters, the simulator will be launched by selecting the RDE button, creating the excitation's wave front (Figure 2).

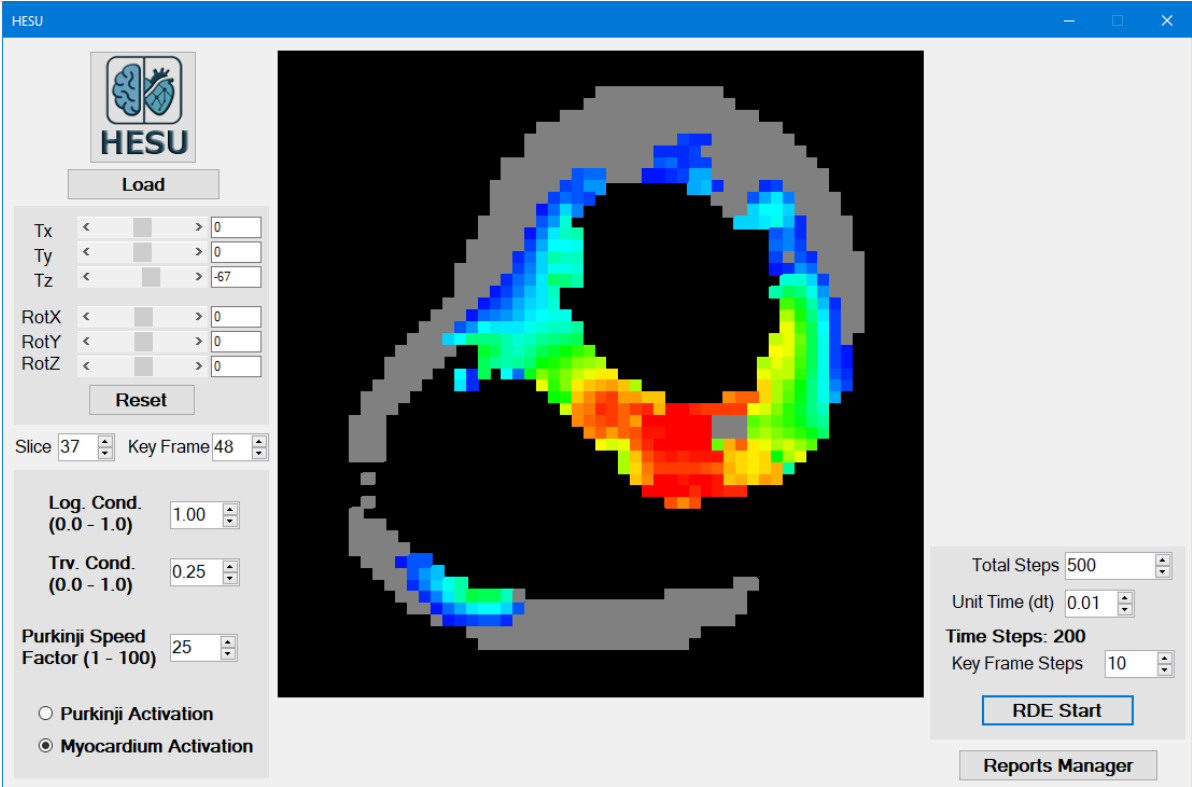


Figure 2. Excitation Propagation.

3.2. Reports Manager

The report manager (Figure 3) will allow to export different formatted output for both excitation propagation and conduction network for use by researchers with a single click (Figure 4).

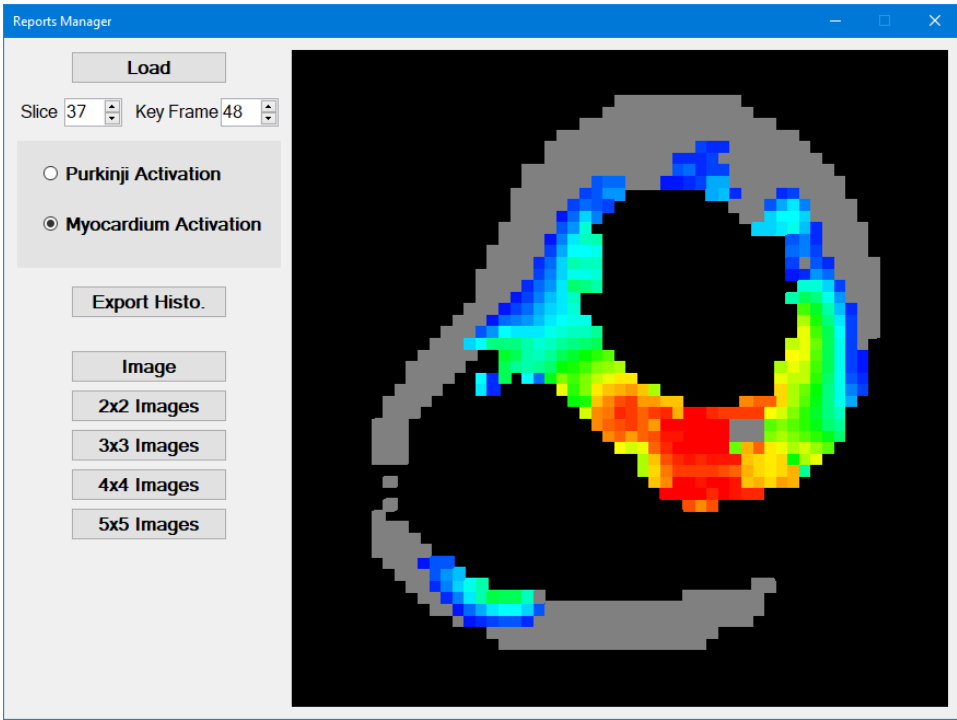


Figure 3. The Reports Manager.

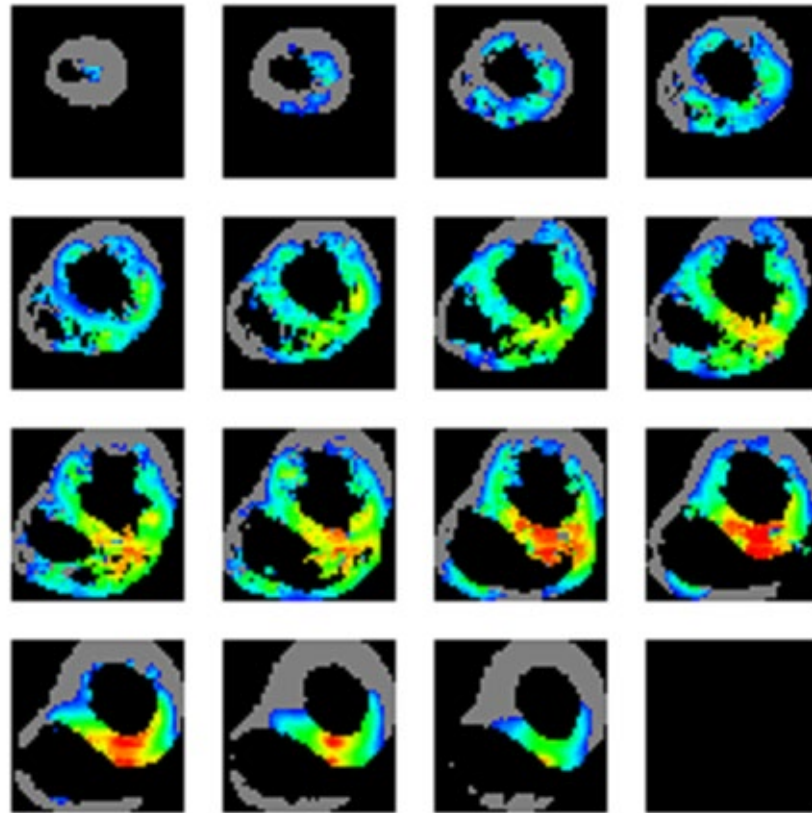


Figure 4. Sample output of the wave front of the heart excitation.

4. Conclusions

The simulation of excitation propagation in the heart must account for the anisotropic nature of myocardial tissue and the detailed structure of the ventricular conduction system. The HE-SU utility offers a comprehensive and customizable simulation environment, integrating DTI-derived fiber orientations and conduction pathways into a reaction-diffusion framework. By enabling user control over key parameters and providing exportable results, this tool facilitates both fundamental research and clinical investigations in cardiac electrophysiology. Future improvements may focus on integrating patient-specific DTI data and coupling electrical simulation with mechanical modeling for a more holistic representation of heart function. **Download Link:** <https://github.com/Ihab-ELAFF/Heart-Excitation-Simulation-Utility-HESU>.

License

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