Modelling the heart and visualization of simulated wavefronts

Roman Ďurikovič*
Daming Wei

Department of Computer Software, The University of Aizu, Aizu-Wakamatsu
Fukushima-ken 965-8580, Japan

Abstract

This work summarizes our experience in working with an anisotropic computer heart model. We propose the heart rotating anisotropy by means of geometrical representation, wavefront propagation using an idea of ellipsoidal neighnorhood, and a visualization system of simulated data. Visualization of this data is crucial to understanding of the unknown mechanisms of heart disease.

Keywords: heart model, heart visualization

1 Introduction

The first simplified, realistically shaped, 3-D heart model was reported by Lorange and Gulrajani [2]. This model did not include the rotation of the fiber orientation and the anisotropic conductivity of the fiber was neglected in calculating body surface potentials. A high resolution model reported by Leon and Horacek [1] included the rotating anisotropy, e.g., myocardial anisotropy, but its geometry was too simple to give realistic electrocardiograms. The present study is based on the work of Wei *et al.* [4] which includes the atria and important detailed electrophysiologic properties including the cell dynamics. The proposed study further improves the model geometry and incorporates rotating fiber orientations. The idea is to use the rotating anisotropy of a fiber into an isotropic heart model and then simulate the electrocardiographic process of the heart.

2 Geometry of the Isotropic Heart Model

The Magnetic Resonance Imaging was used to produce computer model of a human heart. The heart placed in an inclined coordinate system with equal axial angles of 60°, is discretized by parallel planes into the discrete volume of $56 \times 56 \times 90$ voxels. Figure 1 shows a frontal cross-section of the heart geometry and 12-neighbors spatial configuration of model voxels. The 12 neighborhood of each voxel allow uniform wave propagation in all main directions.

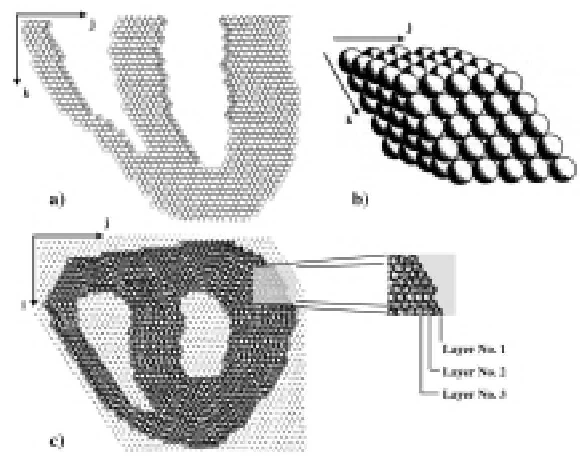

Figure 1: Geometry of the heart model. a) A frontal cross-section, *p* denoting Purkinje fibers. b) Discretized coordinate system. c) Layered structure of a horizontal cross-section.

3 Adding Anisotropy into the Model

For the sake of simplicity the following assumptions are used

1. The myocardial fibers of the ventricles have a layered structure, characterized by a family of nested like ellipsoids extending from endocardium to the epicardium.
2. All fiber orientations parallel to each other within one layer.
3. The fiber orientations change about 90° with increasing depth from outermost layer (the epicardium) to the innermost layer (the endocardium).

The first step in adding the rotating anisotropy is to introduce layers in the model by a thinning algorithm continually applied to the model from outside to inside. The

*roman@u-aizu.ac.jp

central part (septum) of the heart model is specially treated so as to make the septal fibers natural extensions of the left ventricle. Note, that the layer is not necessarily the closed surface in discrete space. The second step is to assign a *fiber plane direction* (FPD) to each layer. It is reasonable to assign an FPD_0 along the geometric *heart axis* to the outermost layer. Then the FPD_0 is rotated counterclockwise in the septal plane to assign FPDs for all other layers given by

$$\alpha(l) = l\frac{A}{N},$$

where l is the layer number, N is the total number of layers, and $A \in (90°, 120°)$ is the total rotating angle between outer and innermost layer. Finally, a fiber direction at a voxel (i, j, k) belonging to layer l is a vector product

$$\mathbf{F_{ijk}} = \mathbf{FPD_l} \times \mathbf{N},$$

where **N** is the normal vector to the layer surface at voxel. Figure 2 demonstrates the process of assigning the FPDs and final fiber directions.

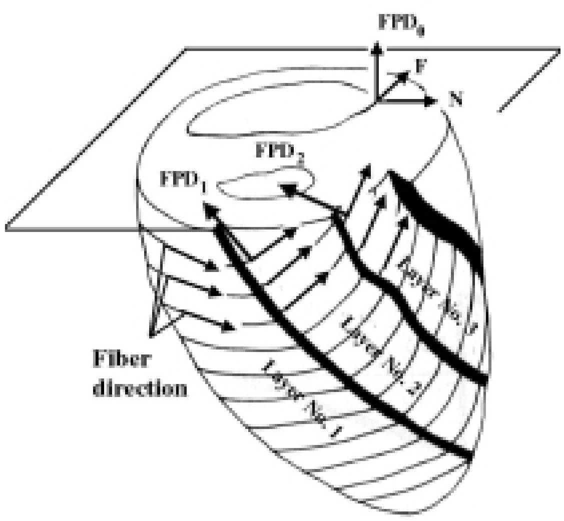

Figure 2: Rotating anisotropy based on fiber plane direction.

4 Propagation Wavefronts

The conductive activation is due to propagation from exciting model cells simulated in discrete time steps $\Delta t = 3ms$.

4.1 The Extend of Propagation

The expansion of propagation around each exciting voxel was defined as ellipsoidal neighborhood with longitudinal semi axis along the fiber direction of that voxel. The longitudinal and traversal axis lengths are

$$r_l = v_F(t)\Delta t \quad (1)$$

$$r_t = k_r r_l, \quad (2)$$

where, $v_F(t)$ is the longitudinal conduction velocity of a voxel at time t, and k_r is the conductivity ratio. Let $< l, n, t >$ is a local coordinate system centered at exiting voxel center, then the extend of propagation is a single time step is an ellipsoid,

$$l^2 R_l^2 + n^2 R_t^2 + t^2 R_t^2 < 1.$$

4.2 Excitable Voxels

All voxels within the ellipsoidal neighborhood, Eq. 4.1, of the exiting voxel are excitable if and only if they satisfy the following principle of refractoriness

$$t - T_{pre} > T_{ARP}(t),$$

where T_{pre} is the starting time of last voxel excitation and $T_{ARP}(t)$ is the absolute refractory period at time t. In other words, there should be a certain time interval between two consequent excitations of the same voxel.

4.3 Conduction Velocity

If the voxel is excitable, e.g., satisfying Eqs. 4.1, 4.2 a conduction velocity $v_F(t)$ along the fiber is assigned to voxel for calculation in the next time-step. The conduction velocity in the direction of a unit vector $\hat{a}$ as proposed in [3] is given by

$$v_F(t) = k\left(\frac{(\hat{a}^T G_i \hat{a})(\hat{a}^T s G_0 \hat{a})}{\hat{a}^T (G_i + G_0)\hat{a}}\right)^{1/2}.$$

In the above equation k is a scaling constant, G_i and G_0 are the diagonal intracellular and interstitial conductivity tensors, respectively, defined as

$$G_i = \begin{bmatrix} g_{it} & & \\ & g_{it} & \\ & & g_{il} \end{bmatrix}, G_0 = \begin{bmatrix} g_{0t} & & \\ & g_{0t} & \\ & & g_{0l} \end{bmatrix}.$$

Values of $g_{it} = 0.0263$ S/m, $g_{il} = 0.278$ S/m, $g_{0t} = 0.133$ S/m, $g_{0l} = 0,222$ S/m were used in the simulation, and the scaling k was adjusted to result in longitudinal and traversal conduction velocities of 63 and 22 cm/s relative to the fiber direction, respectively, which are close to experimental measurements.

5 Visualization and Examples

The system consists of three major parts: a model editor, a simulation program and a visualization program. The model editor enables user to easily construct a heart model from the Magnetic Resonance Imaging sections. In this step user can change the electrophysiological parameters to suit the problem. The simulation program then calculates the propagation sequence, and visualization shows the results in two or three dimensions. The finished system run on conventional PC's.

Activation waves of a horizontal and a frontal cross section for the isotropic and anisotropic models are show in Fig. 3. The main difference between the isotropic and anisotropic models is found in excitation time between layers. This is due to the slow conduction velocity along the transversal directions in the anisotropic model.

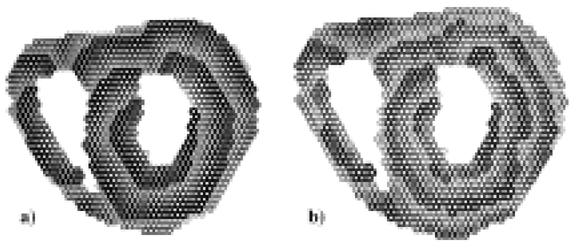

Figure 3: Excitation sequence in the horizontal cross-section of the normal heart. a) Isotropic model. b) Anisotropic model. Each increase in thickness of the circle represents 6 ms.

6 Conclusions

Few ideas have been shown that were used during the implementation of whole-heart model. As for visualization it seemed useful to be able to position the observer at various viewpoints and examine the propagation wavefronts. The combination of 2-D wave propagation within the slice and 3-D propagation on the heart outer surface was implemented to get a better understanding of wavefront positions relative to the heart mass.

References

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