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Electrophysiological Heart Simulator Equipped with Sketchy 3-D Modeling

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Chapter Overview. We present an electrophysiological heart simulator equipped with sketchy 3-D modeling interface. It has been tedious and time-consuming to create the shape of heart for use it in the simulator. In this study, we developed a new simulator that is combined with a sketch-based 3-D modeling interface for the shape transformation. We also developed a semiautomatic method in order to save labor for pre-process of the simulation. The sketchy 3-D modeling interface increases the facility of computer simulation.

Key Words. Electrophysiology, Simulation, and Modeling

1. Introduction

To better understand the mechanisms of fatal arrhythmias, we had previously developed a sophisticated human ventricular-shaped model with the use of computational techniques and visualization technology [1]. The 3-dimensional model contains about 5.64 million volumetric myocardial units, of which membrane kinetics was represented by the Luo-Rudy-1 equations (LR1) [2]. The LR1 consists of the nonlinear ordinary differential equations with 8 variables, based the ionic channel activities of ventricular myocardium. We had developed an electrophysiological heart simulator for solving the differential equations holding about 45 million variables in total, and had implemented the actual calculation on a high-performance supercomputer. Using this simulator, we had simulated physiological electrocardiogram, and also had visualized the various electrophysiological phenomena of arrhythmias in our ventricular-shaped model.

The simulation technology should be applied to the clinical use in the future, and therefore it is imperative that we can use an individual ventricular-shaped model based on the patient's data, and can execute the simulation as quickly as the need arises. As the computer hardware and software technology are progressing rapidly, it is possible to execute the electrophysiological heart simulation more quickly and precisely. However, the preliminary setup is required before calculating the simulation. We have to preliminarily construct the individual shape of patient's ventricles. Not only the acquisition of patient's 3-D data but also the transformation of the volumetric data is important in order to simulate heart disease such as a morphological abnormality like hypertrophic cardiomyopathy. However, skilled operations are needed to transform the volumetric data. We consider that the shape-transformation could be an obstacle to executing the simulation using the individual data. Furthermore, we have to preliminarily determine the parameter setting of ionic channel activity, the excitation sequences of the ventricular subendocardial layer, the position of extrasystole in the ventricular-shaped model, and so on. The subendocardial excitation sequences are key in substitution for incorporating an actual Purkinje fiber network in the model. We had manually built the subendocardial excitation sequences based on the references of real human ventricles [3]. When we use the individual heart shape in the simulation, we need to set up some parameters and embed the subendocardial excitation sequences in the ventricular-shaped model. However, such pre-processes require a lot of tedious work and time. We consider those pre-processes to be potential obstacles to the repetitive trial simulation.

In this study, we developed a new electrophysiological heart simulator that has been combined with a sketch-based interactive 3-D modeling interface for the shape transformation, and with a semiautomatic method to save labor for pre-process of the simulation. This study's objective is different from the former large-scale simulation performed on the high-performance supercomputer. Instead, it is a simple, real-time simulation combined with an interactive modeling interface. The aim of this study is not to perform an accurate and detailed simulation, but to enhance the capability of the computer simulation by using a 3-D modeling interface.

2. Method

2.1 Sketchy 3-D modeling

Our new simulator equips a sketchy 3-D modeling interface for the transformation of ventricular volumetric data. The 3-D modeling interface is based on the "Teddy" [4] software. Teddy is a sketch-based interactive, quick and intuitive 3-D modeling software. When the user draws 2-D freeform strokes interactively on the display like sketching, the system infers the user's intent and executes the appropriate editing operations (Fig.1). Teddy is suitable for the rapid construction of simple and approximate models.

By using the Teddy software, we can construct a simple ventricular model very quickly (Fig.2). First, the user draws a closed stroke on a blank canvas (Fig.2(1)), and then the system automatically generates plausible 3-D polygonal surfaces (Fig.2(2)). Next, the user draws a stroke that runs across the object, and then the system cuts the object on a plane that de-fined by the viewpoint and the stroke (Fig.2(3)). Fig.2 (5) and Fig.2 (6) show the digging operation by the two strokes. In this way, we can obtain a rough shape of ventricles within minutes.

We can also edit the object after loading pre-existing shape data. Figure 3 shows the transforming operations of the ventricular model that obtained from a real human volumetric data. In this study, we added the "expand" operation to original Teddy software as a suitable operation for this study. Using the expanding operation, we can expand the ventricular thickness, assuming the hypertrophic cardiomyopathy.

The sketchy 3-D modeling interface was written in Java™ and we can create and modify the model interactively on an ordinary personal computer (PC).

2.2 Semiautomatic pre-process method for the simulation

Next, we obtained a ventricular model as voxels converted from the polygonal data. And we extracted the subendocardial layer automatically from the ventricular volumetric data by using image-processing techniques e.g. region growing method. Then we built the excitation sequences onto the extracted subendocardial layer by manually specifying the earliest excitation sites, which correspond to the distal ends of the left and right Purkinje bundles. Finally, we defined the extrasystole position for the arrhythmic simulation.

Fig. 1. Sketchy 3-D modeling interface on a Tablet PC.

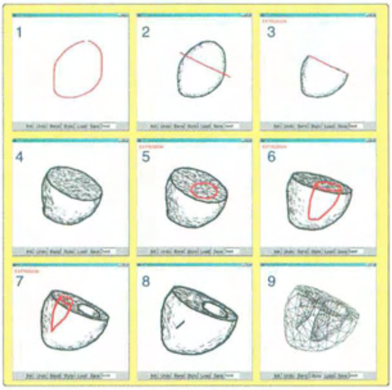


Fig. 2. Creating a simple ventricular model by the sketchy 3-D modeling, (1-8) Create, cut, and digging operations by input strokes (red), (9) A generated object with mesh display.

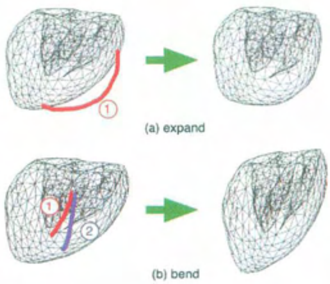


Fig. 3. Modifying the actual human's ventricular model, (a) expanding the thickness by one input stroke (red), (b) bending the model by two strokes (red and blue).

2.3 Electrophysiological heart simulator on a standard PC

We have developed new application software that implements the simple electrophysiological heart simulator on a standard PC. By using this software, we can execute the simulation immediately after modeling the shape of the heart and we can visualize the results in real-time.

The simulation software handles ventricular volumetric data as 64x64x64 voxels. The membrane kinetics of those myocardial units is represented by the FitzHugh-Nagumo equations (FHN) [5, 6]. The FHN consists of the nonlinear ordinary differential equations with 2 variables and needs lower computational resource than LR1. The FHN is not directly based on the ionic channel activities of ventricular myocardium, but it gives an approximate representation properly for our simple electrophysiological simulation on a PC.

Our program's screenshot is shown in Fig.4. In our new application, we can execute the simulation using two models simultaneously for easy comparison. The Marching Cubes [7] method is used for visualizing ventricular volumetric data. The simulator was created using C++, OpenMP™, OpenGL® and so on.

3. Results

We run the sketchy 3-D modeling interface and the simple electrophysiological simulator on the same PC. The original shape of ventricles was constructed based on geometrical data of the actual human ventricle (Viewpoint DIGITAL™). By using the sketchy 3-D modeling interface, we were able to create some shape-transformed ventricular models easily and quickly. Using our new simulator, we built the excitation sequences semiautomatically onto the subendocardial layer of the ventricular models. Then we were able to observe the visualized results of the electrophysiological simulations immediately. We observed various electrophysiological phenomena (dissipation, breakup, sustainment, meandering, and so on) in the difference of the heart shapes (Fig.5). Table 1 shows the time required for numerical calculation and visualization per 1 frame on the PCs. The frame rate is from 0.5 to 2 frame/sec.

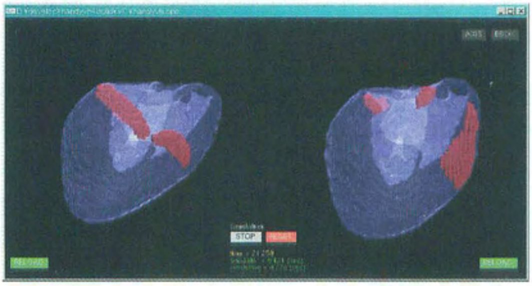
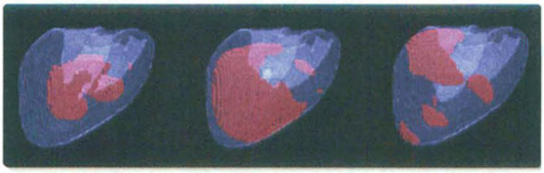
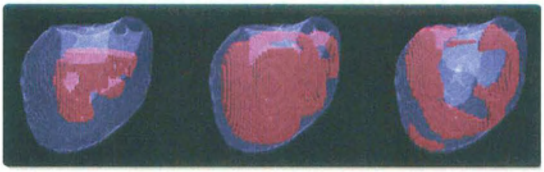


Fig. 4. Electrophysiological heart simulator on a standard PC.



(a) original model



(b) transformed model

Fig. 5. Various electrophysiological phenomena by difference of the ventricular shapes.

Table 1. The time required per 1 frame on a simple simulator

MPU	OS	Calc. Time	Vis. Time
Xeon/2.8GHz x2	GNU/Linux	0.29s	0.11s
Pentium4-M/2.2GHz	Windows2000	0.45s	0.06s
PowerPC7445/867MHz	Mac OS X	1.48s	0.42s

4. Discussion

As computer software and hardware technology is advancing rapidly, electrophysiological simulation has been able to become more precise. Meanwhile construction processes of the ventricular-shaped model need more consideration. Our sketchy 3-D modeling interface and the semiautomatic pre-process method save us unnecessary labor and enable us to create more effective simulations using the individual and transformed models.

Usually CAD (Computer Aided Design) system is usually used for modeling the shape of heart in the computer simulation. CAD system is suitable for precise modeling, but it has some weak points when dealing with rotund objects like organs. Image-processing techniques are used for generating a 3-D volumetric organ model from MRI or CT data, but it is difficult to automatic extraction the target region from image sequences.

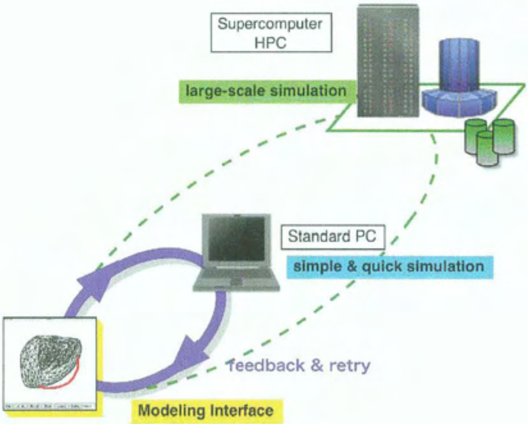


Fig. 6. Overview of this study's concept: increase the facility of computer simulation.

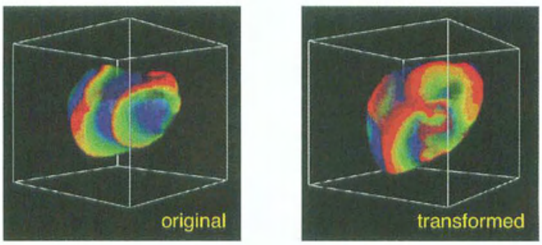


Fig. 7. Visualized results of large-scale simulation on supercomputer.

Some time-consuming procedures are necessary for obtaining a 3-D model. In this study, because we have integrated the modeling interface with the simulator, we can handle the shape transformation of the ventricular model easily in the simulation research. For example, we can "expand" the shape of the model with only one stroke. Then we can execute the simulation easily with estimating morphological abnormalities, such as hypertrophic cardiomyopathy. We observed that the ventricular shapes do influence the electrophysiological phenomena.

The sketchy 3-D modeling interface is suitable for not only transforming the existing model, but also creating a new model. In the future, the sketchy interface can be applied to assist the extraction procedure from medical image sequences obtained from MRI, CT and echocardiography.

Usually, a large-scale electrophysiological simulation requires powerful computational resource and much time. Our simple system that can be created on an ordinary PC has some limitations in accuracy and scalability because of limited computational resources for numerical equations representing myocardial membrane kinetics. However, our system has unique merits that can be observed in real-time as soon as modeling the shape of heart has been completed. Our system enables us to execute repetitive trial simulation and makes it easy to observe the significant data. It also enables us to increase the potential for a large-scale precise simulation (Fig.6). Additionally, we ran a large-scale electrophysiological simulation that was previously developed. We used an NEC SX-6/8A supercomputer for the computation. The polygonal data of the transformed ventricular model were converted to 300x300x300 voxels and each unit was represented by the LR1. LR1 is more complex than FHN and needs remarkably higher computational resources. Required time to perform a 1,000msec simulation was about 3 hours. We used volume-rendering techniques [8] for visualizing the results. In the large-scale simulation, we observed various electrophysiological phenomena in the difference of the heart shapes. In Fig.7, the original shape (left) became sustainment caused by extrasystole, and the transformed shape (right) changed over from sustainment to breakup.

5. Conclusion

Integrating the sketchy 3-D modeling interface with the electrophysiological heart simulator enables us to save the labor required for repetitive trial simulations using the individual and transformed ventricular models. Our system equipped with a sketchy 3-D modeling interface enables us to increase the facilities of the computer simulation. We expect that, in the future, our simulator would be used for the research and clinical purposes, and also as an educational tool for medical staffs.

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References

1. Nakazawa K, Suzuki T, Ashihara T, et al. (2000) Computational analysis and visualization of spiral wave reentry in a virtual heart model, Clinical Application of Computational Mechanics to the Cardiovascular System, Yamaguchi T (ed), Springer: 217–241
2. Luo CH, Rudy Y (1991) A model of the ventricular cardiac action potential: Depolarization, repolarization, and their interaction, Circ Res 68:1501–1526
3. Cassidy DM, Vassalo JA, Marchlinski FE, et al. (1984) Endocardial mapping in humans in sinus rhythm with normal left ventricles: activation patterns and characteristics of electrograms, Circulation 70:37-42
4. Igarashi T, Matuoka S, Tanaka H (1999) Teddy: A sketching interface for 3d freeform design, ACM SIGGRAPH'99, Los Angles, ACM, pp.409–416
5. FitzHugh R (1961) Impulses and physiological states in theoretical models of nerve membrane, Biophysical J 1:445-446
6. Nagumo J, Arimoto S, Yoshizawa S (1962) An active pulse transmission line simulating nerve axon, Institute of Radio Engineers 50:2061-2070
7. Lorensen WE, Cline HE (1987) Marching cubes: A high resolution 3d surface construction algorithm, ACM SIGGRAPH'87, Los Angles, ACM, pp.163-169

8. Levoy M (1988) Display of surfaces from volume data, IEEE Computer Graphics and Applications 8(3):29-37