Cardiac Arrhythmia Visualization in a Virtual Heart for Electrophysiology Education

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Abstract
The 3D cardiac arrhythmia visualization model in this paper was developed to assist medical students and fellows in understanding the underlying electrophysiology of cardiac arrhythmias and their treatments. In this detailed cardiac model, the user can freely move to any position of the heart and observe it from any point of view. A transparent mode is applied to facilitate a more detailed exploration of the heart. Two common types of arrhythmias, atrial flutter and atrioventricular nodal re-entrant tachycardia as well as the effects of catheter ablation treatment are represented in this model. VR920 3D glasses facilitate virtual reality immersion. The model is expected to help users to visualize abstract electrophysiology concepts and procedures, raise medical education and training levels, and, ultimately, benefit patients through better training outcomes.

1. INTRODUCTION
1.1. Background
Arrhythmia is an abnormality in which the rhythm of heart electrical activity is irregular, faster or slower than the normal condition. An arrhythmia is called tachycardia when the heartbeat is too fast (more than 100 beats per minute); it is called bradycardia when the heartbeat is too slow (less than 60 beats per minute). Arrhythmias can happen at any age: some are hardly perceptible and not life threatening; some can be very serious and may lead to cardiac arrest. When the cardiac arrest occurs, the heart cannot maintain normal blood circulation to the body. Brain is injured if there is not enough oxygen and nutrient supply. When the arrhythmia is clinically significant, the patient should have a treatment plan. Treatments for arrhythmia include a physical maneuver, medications, electrical cardioversion, and catheter ablation therapy [1].

Arrhythmias involve a set of complicated and invisible phenomena. Their electrophysiology is widely considered difficult to be understood by medical students. In traditional training, students trying to understand the concepts of electrophysiology need to convert the words that they heard and read, as well as the static pictures and diagrams that they see in a textbook into dynamic processes that they process in their brain [2]. Modern training approaches, such as the one developed in this paper, built with computer and information technologies provide dynamic models and attempt to make the learning process more efficient. Often, students are highly enthusiastic about multimedia learning resources.

1.2. Current research
Currently, there are several cardiac models used for education. For example, Hurmusiadis worked on a prototype of virtual heart organ for clinical skills training [3]. This model has high resolution and uses downloaded myofibril orientation data as well as a cellular automaton method to model the propagation of action potential through the heart. This model also designates cells in their cellular automata model as “dead” in order to capture and visualize the causes of arrhythmias in the heart.

Additionally, Cherry et al. focus on electrical spiral and scroll waves visualization on the heart tissue from experimental and simulated data [4]. This model simulates the electrophysiology of the heart under arrhythmias. It also demonstrates how ablation in certain areas affects the arrhythmia electrophysiology. Both, this model and the model depicted by Hurmusiadis represent the electrophysiology of the heart using color gradients through the heart. The model presented in this paper focuses on depicting the conduction pathways.

Lessard et al., represent a 2D heart picture, Lewis diagram and electrocardiogram (ECG) synchronously as a tool to teach students how to interpret ECG results; in addition, an interactive quiz was designed to assess the learners [5]. J. Aguado-Sierra et al. had produced a heart model of specific patients’ hearts using ultrasounds to obtain the shape of the heart, with standard myofibril orientations overlaid onto this representation [6]. Electrocardiograms were then used to map the electrical activity of that patient onto their heart representation. This model is a static representation of a patient’s heart with the intended use of aiding in diagnosis and treatment of those patients.

Additionally, F. Vadakkumpaden et al. processed a structural MR image of a heart to generate a 3D mesh model. They overlaid this mesh with fiber orientations from data.
taken from a DTMR image [7]. Then, they constructed the Purjune system onto this model from the original MRI data. Once the reconstruction was complete, this model was used to display arrhythmias and the effects of defibrillation on the heart.

The zSpace system, which is an interactive virtual reality setup, was developed by zSpace, Inc. [8]. It includes a special monitor with dual tracking cameras, polarized 3D eyewear and a tracking pen. It is a complete but highly expensive virtual reality tool.

The model, we present in this work is dynamic and three-dimensional. It is able to represent several arrhythmia phenomena and ablation treatment effects. Furthermore, the model can interface with virtual reality, 3D glasses, providing the users with an immersive learning experience. Unique to the model presented in this paper, as compared to the models discussed above, is the method of visualizing electric potential propagation through the heart, the ability of the user to interact with the model by placing ablation spots in the heart tissue and watching the effects of those ablations to the electric pathways, as well as the virtual reality based heart visualizations.

2. BASIC MODEL

The prototype of the model has been built. The major functions are described below.

2.1. Heart model

Heart is the organ that pumps blood through vessels to the body. The muscle of the heart contracts at a certain rhythm. It consists of four chambers. The two upper chambers are atria, which are in charge of receiving and collecting blood; the two lower chambers are ventricles, for pumping blood out of the heart to the whole body [9].

The original model structure data and texture in our cardiac model came from Dosch Design [10]. We rescaled and converted the data into the obj file format, and redesigned it in the C++ programming language and OpenGL open source computer graphic library (as shown in figure 1). Our model provides an interactive control of the camera, which can freely move around, rotate and zoom in the 3D space. The control modes include the keyboard, mouse, and 3D glasses. The user can observe the model from any point of view, and move anywhere around the heart, both inside and outside of it.

A transparent mode was also designed for our system. We attached the parameters of transparent value for each part of the heart model. In this mode, any part of the heart can be semi-transparent at any user-defined scale as shown in figure 2, in which the right atrium, left atrium and left ventricle are semi-transparent. In this way, users can observe what happens inside the heart from any outside visual point. This helps them to form an overall concept of cardiac electrophysiology. Furthermore, any parts of the heart can be removed and recovered as shown in figure 3, in which the right atrium, left atrium and the left ventricle have been removed. This feature makes the model more flexible in presenting anatomical features.

Figure 1. Cardiac model

Figure 2. Transparent

Figure 3. Parts removed
2.2. Normal conduction system

The electrical conduction system is the controller that makes the chambers contract and relax to pump blood through the heart. It controls the rhythm of the heartbeat.

For each normal heartbeat, the electrical impulse originates from the sinus node, also called sino-atrial node (SA node), which is located in the top of the right atrium. The rate of heartbeat is normally controlled by the SA node. Therefore, the normal rhythm is called the sinus rhythm. The electrical impulse spreads through the right and left atria and causes them to contract. Then, the impulse arrives at the atrioventricular node (AV node), which is the only electrical connection between the atria and ventricles in normal conduction. The AV node delays the signal spreading to ventricles so that the ventricles contract later than the atria, allowing the ventricles to fill with blood before contraction. The impulse then spreads through the bundle of His and Purkinje fibers, which is the end of conductive tissue, leading the impulse to deeper tissue, causing the ventricles’ contraction [11]. This process is shown in figure 4 [12], and its ECG (electrocardiogram) is shown in figure 5.

![Figure 4. Normal conduction system](image)

![Figure 5. ECG of normal condition](image)

2.3. Atrial flutter

The atrial flutter is caused by a reentry impulse, which is initiated by a premature atrial impulse and propagated due to a different refractory period of the atrium’s tissue. The reentry impulse keeps moving in a circuit, and stimulating the atrium to contract for each cycle of the loop by more than 250 beats per minute [13].

In the right atrium of our model, the flutter reentry impulse is visualized as a track which is led by a signal ball with a trail circling around as shown in figure 7. The trail represents the refractory period on tissue. The user can adjust the speed of the signal and the length of the trail, which can be used to simulate the drug effect of tachycardia. When tachycardia is treated with Ic class drugs, such as Flecaïnide, the conduction velocity of the signal will become slower; when tachycardia is treated with III class drugs, such as Dofetilide, the tissue refractoriness period will become longer.

![Figure 7. Atrial flutter](image)
2.4. Ablation

The catheter ablation therapy is an invasive operation that eliminates fast or irregular heartbeats. During this procedure, a catheter is inserted into the heart chamber. It destroys a tiny area (about 1/5 inch) of heart muscle by high frequency energy. Then, the electrical pathway of abnormal rhythm is disrupted, or the abnormal impulse is blocked. It is most often applied to treat atrial flutter, atrial fibrillation, supraventricular tachycardia, and Wolff-Parkinson-White syndrome. It has a very high success rate [14]. In our model, we apply catheter ablation to illustrate the atrial flutter case. The user can create ablation “dots” (marks) on the pathway of the signal circle. In figure 8, the gold dots at the bottom, are tissue ablation spots. In this case, the ablation area is not large enough, and the ablation line is incomplete to stop the reentry impulse. However, in figure 9, ablation successfully stops the impulse, and the atrial flutter is eliminated. We simulated a prototype of intracardiac electrograms on the model by planting several electrode probes to detect electric potential on the tissue, as shown in figure 10. The intracardiac electrograms can guide the ablation catheter to the right position and check the effect of treatment. [15]

Figure 8. Incomplete ablation line

Figure 9. Correct ablation

2.5. AVNRT

Atrioventricular nodal re-entrant tachycardia (AVNRT) is a common type of supraventricular tachycardia (SVT), which is a category of tachycardia originating from the location above the bundle of His in the heart [16]. It is caused by the reentry impulse around the AV node. In patients with AVNRT, there are two signal pathways in or close to the AV node: a fast and a slow pathway. Normally, because of different refractory periods, the impulse signal passes through the fast pathway and is unable to pass through the slow pathway. However, when there is a premature atrial contraction between two sinus rhythm impulses, the signal will be blocked in the fast pathway but will pass through the slow pathway, and form a reentry circle around the fast pathway and the slow pathway. This reentry impulse will stimulate the atria to contract. In our model, AVNRT is visualized as a dynamic procedure as in figure 11, and the ablation effect is shown in figure 12.

Figure 10. Intracardiac electrograms

Figure 11. AVNRT
2.6. Connection with 3D glasses

Virtual technology is rapidly developing and is widely recognized for its tremendous potential in professional training and entertainment. In our system, we use iWear VR920 from VUZIX 3D glasses. They offer a high resolution (1024 x 768 at 60 Hz) LCD screen for each eye inside the glasses, and the vision effect appears as 62-inch screens viewed from a distance of 9 feet. When we stereoscopically render the model and output two slightly different images to the right and left side of the glasses respectively, the user gets the full 3D effect. The glasses have 3 magnetic sensors and 3 accelerometers inside. Therefore, the yaw, pitch and roll moving data are captured to get head tracking. It means that the 3D model in the glasses can follow the motion of the user’s head. Thus, a realistic experience of a “journey” inside the heart is created.

3. CONCLUSION

Three dimensional visualization techniques can facilitate the understanding of the principles of electrophysiology. In our project, a detailed and interactive cardiac model was built; the propagation of normal conduction system, sinus beat, and two common types of tachycardia was presented. The effects of Ic class drugs, III class drugs, and catheter ablation treatment was provided interactively. The head tracking virtual reality technique was supported in this model through the connection with VR920 3D glasses. We expect our work to better attract learners’ attention and to provide higher efficiency of learning. Medical students with better professional training will contribute to reduce medical cost and clinical errors; in addition, patient outcomes are be expected to improve.

In the future, it is important for us to improve the model. The processes of how tachycardia originates will be developed for cases of premature atrial beat, atrial flutter and AVNRT. More types of arrhythmias will be presented on this model. ECG data and intracardiac electrogram data will be shown synchronously with dynamic tachycardia propagation in order to help learners in connecting the concept of 3-dimensional arrhythmia mechanisms with the clinical ECG recording. We are considering applying this model on more advanced virtual reality devices.

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References
Biography

Dong Xing received the MS and BS degree in Biomedical engineering from Southern Medical University, China. Currently, he is working toward the master degree in electrical and computer engineering at The University of Arizona. His active project is on 3D cardiac arrhythmia visualization.

Dr. Jerzy Rozenblit is University Distinguished Professor, Raymond J. Oglethorpe Endowed Chair in the Electrical and Computer Engineering (ECE) Department, and Professor of Surgery in the College of Medicine at The University of Arizona. From 2003 to 2011 he served as the ECE Department Head. During his tenure at the University of Arizona, he established the Model-Based Design Laboratory with major projects in design and analysis of complex, computer-based systems, hardware/software codesign, and simulation modeling. The projects have been funded by the National Science Foundation, US Army, Siemens, Infineon Technologies, Rockwell, McDonnell Douglas, NASA, Raytheon, and Semiconductor Research Corporation. Dr. Rozenblit had served as a research scientist and visiting professor at Siemens AG and Infineon AG Central Research and Development Laboratories in Munich, where over he was instrumental in the development of design frameworks for complex, computer-based systems. Currently, jointly with the Arizona Surgical Technology and Education Center, he is developing computer guided training methods and systems for minimally invasive surgery. Co-author of several edited monographs and over two hundred publications, Jerzy holds the PhD and MSc degrees in Computer Science from Wayne State University, Michigan, and an MSc degree from the Wroclaw University of Technology. He presently serves as Director of the Life-Critical Computing Systems Initiative, a research enterprise intended to improve the reliability and safety of technology in healthcare and life-critical applications.

Samantha Bernau received the BS degree in biomedical engineering from The University of Arizona and is currently working towards the MS degree in electrical and computer engineering at The University of Arizona. Her present research interests include biomedical technologies.

Dr. Peter Ott is Associate Professor of Clinical Medicine and Director of the Cardiac Electrophysiology Laboratory and Arrhythmia services at the University of Arizona. A native of Germany, he received his medical degree from the University of Heidelberg in 1987 and completed his medical residency training at the University of Arizona. He served one additional year as Chief Medical Resident and then moved to Denver Colorado where he completed Fellowship training in Cardiology at the University of Colorado, which included one year of electrophysiology training. He returned to Germany for two years working in Cardiology/Electrophysiology at a large tertiary referral center for Cardiology in the Southwest of Germany. He then transferred to the University of Utah in Salt Lake City for additional training in Cardiac Electrophysiology before returning in 1999 to the University of Arizona to his present position. Dr. Ott is board certified in Internal Medicine, Cardiovascular Diseases and in Clinical Cardiac Electrophysiology. His clinical expertise is the management of patients with cardiac arrhythmias, including catheter ablation therapy and device therapy (implantable defibrillator and pacemaker). He has performed over 5000 invasive electrophysiology procedures including cardiac pacemakers, defibrillators and catheter ablation procedures. His research interests are the electrophysiologic effects of heart failure, treatment of atrial fibrillation and treatment of cardiac arrhythmias with catheter ablation.