A Virtual Reality for Catheter-based EPS based on Whole-heart Model

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Abstract. This paper presents an introductory description of a development of virtual reality for computer simulation of catheter-based electrophysiology study (EPS). We first summarize a state-of-the-art model of the heart and computer simulation of body surface electrocardiograms (ECG), giving a latest example in simulation of Brugada syndrome. We summarize the extension of the whole-heart model in order to compute intracardiac electrograms for simulation of catheter-based EPS. We then introduce a development of virtual reality, called virtual EP Lab, which links the heart model to input device through a computer graphics interface. The virtual EP Lab may be useful for the purposes of medical training in learning catheter operation and clinical EPS.

Keywords: Electrophysiology study (EPS), Catheter, Whole-heart Model, Computer simulation, Virtual Reality.

1. Introduction

Recent years, catheter-based Electrophysiology Study (EPS) has been one of the most important means to quantitatively evaluate the electrophysiological condition of the heart. It is, however, usually difficult to master the EPS technique for beginners because it needs not only catheter manipulation skill but also deep understanding of theoretical and clinical electrophysiology. We do not find any existing training system that can be used for both catheter manipulation skill and electrophysiology.

Whole-heart modeling and computer simulation of electrocardiograms (ECG) have been long studies for our group [1-3]. For many years, our heart model was aimed at computer simulation for body surface ECG, linking clinically-comparable body surface ECG to undergoing bioelectric phenomena within the heart. The heart model is recently extended for simulation of intracardiac ECG potentials to that can be compared with catheter-based clinical EPS. We are further developing a virtual reality that links catheter emulators to our ECG simulation system. The virtual reality, called Virtual EP Lab, is introduced in this paper.

2. Whole-heart Modeling for Computer Simulation of Body Surface ECG

The details of the-state-of-the-art heart model principle for body surface ECG simulation are described in our previous literature [1-3]. The main features are summarized as follows:
- A realistic-shaped heart model incorporating atria and ventricles
- A finite element model covering all types of cardiac cells
- Incorporating rotating anisotropy of ventricular myocardium with cell-by-cell fiber directions
- Incorporating detailed electrophysiological properties categorized by action potential, conduction velocity, automaticity, and pacing
- Comprehensive algorithms in simulating excitation and repolarization based on the Huygens’ principle
- Incorporation of cell dynamics governing mechanisms for cardiac arrhythmias
- A boundary element algorithm in computing body surface potentials.

So far, a number of simulations based on this model have been published, including mechanism of clinic ECGs in waveforms [4, 5] and rhythms [6-8]. In Fig. 1, we show one example of our latest results in simulation of Brugada syndrome (BS) using this model. The model was created by adding
abnormal cells in the region close to the right ventricular outflow track (RVOT) as shown in Fig. 1 (a), and setting up action potential of Brugada type to the cells according to literature [9]. The 12-lead ECG in Fig. 1(b) shows accentuation of J-wave and apparent ST-segment elevation in the right precordial ECG leads, which are principal signs of the BS. An important ECG feature of BS is the increased risk of ventricular fibrillation (VF) leading to sudden cardiac death. Figure 1(c) gives an example of VF induced by 5 trains of electrical stimuli applied to the heart model [10].

![Diagram of BS cells and ECG leads](image)

**Figure 1:** Simulation of body surface ECG of atypical Brugada syndrome (BS). (a) illustrates the locations of BS cells in the heart model. The right part is a cross-section of the heart model. Model cells of different colors represent ventricular muscle, Purkinje fiber, and BS. RV and LV denote right and left ventricles, respectively. The arrow points to a location where stimuli are applied resulting in simulated ECG of VF shown in (c). (b) shows simulated 12-lead ECG featured with J-wave and ST-elevations. See also text for details.
3. Computer Simulation of EPS

For simulation of EPS, it is necessary to compute intracardiac ECG potentials inside the heart chambers. For this purpose, we extended the volume conductor model of previous heart-torso model by adding endocardial surface boundaries and volumes of intracavitary regions. In this way, the intracardiac potentials inside the heart chambers emulate catheter-measured intracardiac potentials. We also extended numerical solutions of boundary element method to involve intracardiac potentials.

Formula (1) is used to solve the volume conductor problem based on the boundary element method [11, 12] applied to a volume conductor model shown in Fig. 2:

\[
\Phi(r') = \frac{1}{4\pi} \int \Phi(r) \cdot d\Omega_{r'} + \frac{1}{4\pi} \int \frac{1}{r} \frac{\partial \Phi(r)}{\partial n} dS
\]

(1)

where \( \Phi \) denotes observation position, and \( n \) is the integration variable on the surface S3 or S4 (see Fig. 2). Bipolar electrograms were further calculated to emulate catheter-measured signals on locations, such as, the high right atrium (HRA), the His bundle (HB), the right ventricle (RV), and the coronary sinus (CS).

We successfully simulated most EPS protocols used in the clinical practice. Figure 3 shows an example of atrial extrastimulus pacing in the model of normal heart.

![Figure 2: The volume conductor model for simulation of EPS. Surfaces of S1, S2, S3, and S4 are the body surface, the epicardial, the right, and left endocardial surfaces, respectively. The volume V1 represents a homogeneous torso model excluding the heart with an average conductivity value of torso. Volumes of V2 through V4 represent the myocardium, and heart chambers with blood. The surface normals ni (i=1–4) point to the outside of the surfaces.](image)

![Figure 3: A simulation of atrial extrastimulus pacing protocol. From top to bottom, the simulated waveforms are body surface ECG of lead I, aVF, and V1, and intracardiac electrograms corresponding to those measured by catheters at HRA (high-right atrium), HIS (His bundle), RV (ventricle) and CS (coronary sinus). This example shows a decremental conduction in the AV node, where the atrial extrastimuli of S1S2 are 360ms - 220 ms.](image)
4. The "Virtual EP Lab"

The heart model and computer simulation system described above is linked to a virtual reality called Virtual EP Lab that mimics the operation and manipulation of catheter-based EPS.

Several input devices are developed. Figure 4 shows an input device with sensors used to emulate the catheter manipulations that employ actual catheters in routine clinical practice. Maximum six catheters can be used in one time to simulate possible EPS situations. The actuator measures immersion length, rotation angle, and bend angle that are necessary for catheter manipulation and transfers these data to a computer graphics system that linked to the actuator.

![Figure 4: An actuator developed to emulate catheter manipulation. Maximum six actual catheters can be used at one time.](image)

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Figure 5 shows a different type of input device using a commercially-available remote controller for game machines (Nintendo© Wii®). With 3-axis accelerometer, a high-resolution, high-speed IR camera, the same actions for the catheter manipulations like translation, rotation, and bending, can be generated and lined to a graphics system. Besides, because of its wireless connectivity (Bluetooth), this device can be simply used in a pervasive environment (classroom, home, and any other conditions) at a very low cost. A possible drawback of this system is the absence of feelings feedback which presents with actual catheters.

![Figure 5: An input device for catheter manipulation training using Nintendo© Wii®. See text for explanation.](image)

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A computer graphics interface was developed to emulate the EPS procedure, as an interface between the input device that mimics the catheter manipulation and the whole-heart model that simulates the electrophysiological mechanism of the heart. Figure 6 shows an example of catheter location in the heart model through the conversation between the input device and the graphics interface. A virtual X-ray algorithm [13] was developed to display the catheter location in the 3D heart-torso model. The catheter movement within the model of vessels is animated by a physics-based simulation. The models of vessels are constructed based on the 3D CT images from a hospital.

5. Conclusion

A virtual reality system for simulation of catheter-based EPS is developed by linking a whole-heart model and a computer simulation system to input devices with which the catheter manipulation can be mimicked. The catheter operation can be virtually performed with the input devices while watching a virtual X-ray camera. Linking to this operation, the EPS protocols are applied to the heart.
models and the body surface ECG and the EPS electrograms are computed and displayed. We believe the virtual EP Lab may be a useful tool in medical training. We also believe this study suggests a new application of heart modeling and computer simulation of ECG.

Figure 6. A virtual X-ray image showing catheter location regarding to a 3D torso-heart model. See text for explanation.

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