

Computer Simulation of Electrophysiology Study based on Whole-heart Models

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Abstract—Computer simulation of Electrophysiology Study (EPS) is realized by employing pacing protocols in EPS with the Wei-Harumi model. Intracardiac electrograms induced by typical pacing protocols—including the basic interval measurement, atrial extrastimulus pacing, ventricular extrastimulus pacing, incremental atrial pacing, and incremental ventricular pacing are successfully reproduced with a model of WPW syndrome. The tests of electrophysiological properties of cardiac tissues, such as the determination of the refractory period, induction of Wenckebach rhythms, and induction and termination of supraventricular tachycardias, are successfully simulated and the simulation results agree with clinical findings. This study demonstrates the feasibility and reliability of the computer simulation of EPS based on the whole-heart model.

Index Terms—Computer simulation, electrophysiology study (EPS), whole-heart model, programmed electrical stimulation

ELECTROPHYSIOLOGY study (EPS) is used to accurately localize the ectopic foci or accessory pathway for completely curing complex cardiac arrhythmias with the catheter ablation [1][2]. Currently, most EPS-related research is based on the analysis of intracardiac electrograms measured during EPS and animal experiments. On the other hand, heart modeling has been an effective approach for the study of cardiac electrophysiology [3][4]. To date, studies on computer simulation of whole-heart model are focused on the reproduction of body surface ECG. As the intracardiac electrograms measured during EPS contain much more accurate and reliable information for the diagnosis of cardiac arrhythmias, we have studied the computer simulation of intracardiac electrograms with the whole-heart model and realized computer simulation of intracardiac electrograms using a model of the WPW syndrome [5]. In this paper, based on our previous research, we employed the whole-heart model for computer simulation of EPS to reproduce the intracardiac electrograms after the programmed electrical stimulation is delivered in the heart. Some typical pacing protocols are successfully conducted in a model of WPW syndrome (Type A); and the electrophysiological properties revealed from the simulated intracardiac electrograms conform to the existence of Kent bundle in the heart model.

I. METHOD AND MATERIALS

A. Whole-heart model

The Wei-Harumi model is employed for the computer

simulation of EPS since this model has been widely distributed and accepted as a start-of-the-art whole-heart model [4][5]. The Wei-Harumi model can simulate the excitation propagation in the atrium, special conduction system, and ventricle for multiple cycles with acceptable computation burden by personal computer. The Wei-Harumi model is composed of many components, including the torso-heart volume conductor model, atrium, ventricle, specialized conduction system, rotating fiber direction, myocardial anisotropy, action potential and propagation, and electric cardiac source. Figure 1 illustrates the model of WPW syndrome (Type A) with a Kent bundle in the left anterolateral wall as described in [4][5] for the simulation of pathological intracardiac electrograms. The time delay of excitation in the Kent bundle is 39 ms, and the refractory period of the Kent bundle in the antegrade and retrograde directions are 400 ms and 180 ms, respectively.

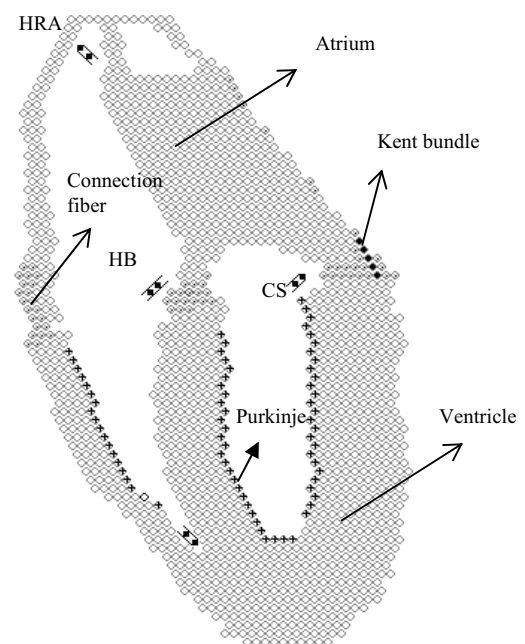


Fig. 1 The frontal cross section of the Wei-Harumi heart model. The locations of the HRA, HB, RV, and Kent bundle are marked.

B. Pacing protocols

For the diagnosis of preexcitation syndrome like the WPW syndrome, the main pacing protocols used in EPS are the basic interval measurement, atrial extrastimulus testing, ventricular extrastimulus testing, incremental atrial pacing, and incremental ventricular pacing. In this paper, the simulations of these pacing protocols are conducted and the corresponding intracardiac electrograms are calculated and analyzed. Among the pacing protocol, the basic interval measurements are to measure the time intervals in the intracardiac electrograms at the sinus rhythm. The extrastimulus testing is composed of a progressively premature atrial extrastimulus (S2) delivered after a train of 6–8 atrial stimuli (S1) in the atrium or ventricle. The main roles of the atrial extrastimulus testing are to test the properties of special conduction system, measure the effective refractory period (ERP) of special conduction system, detect the existence of accessory pathway, and induce the supraventricular tachycardia (SVT). The incremental pacing is also commonly used in EPS for the observation of excitation propagation in the heart during steady-state conditions, test the conduction in the special conduction system (SCS), and induce the SVT. The incremental pacing is conducted by delivering a train of stimuli (S1) at a constant cycle length [1], [2].

C. Computer simulation of whole-heart model

The Wei-Harumi model uses the electrical propagation of Huygens' type to simulate the depolarization and repolarization of myocardium cell models, where there are two types of activation model units: "conductive" and "non-conductive." The non-conductive activation is concerned with units of pacemaker, whose activation is obligatory whenever the firing time comes. The conductive activation is due to propagation spread from exciting model units. An ellipsoidal wavelet based on the local fiber direction, together with some parameters, is used to distinguish whether a model unit can be activated or not. The propagation direction of model cell in the antegrade and retrograde directions is controlled with electrophysiological parameters. Studies of Wei et al. [3][4] have proved that the propagation of Huygens' type can accurately reproduce a variety of electrocardiographic phenomena in complex situations.

D. Calculation of intracardiac electrograms

The equivalent dipole density source J_s , i.e., the electric cardiac source, can be derived from the transmembrane action potentials simulated in the computer heart model with the bidomain approach [3]. With the assumption at a quasistatic electric field, the following Poisson's equation governs the potential distribution Φ in a torso-heart model with isotropic conductivity σ [3]:

$$\nabla \cdot \sigma \nabla \Phi = \nabla \cdot J_s. \quad (1)$$

Intracardiac electrograms are calculated with the boundary element method to a torso-heart volume conductor model, where the body surface, epicardial surface, right endocardial surface, and left endocardial surface are divided into 344, 1002, 307, and 278 nodes, and 684, 2002, 610, and 552 triangles. The common bipolar intracardiac electrograms are

HRA (high right atrium) electrograms, HBE (His bundle electrograms), RV (right ventricle) electrograms, and CS (coronary sinus) electrograms measured with electrodes, whose locations on the electrode catheter are illustrated in Fig. 1.

II. RESULTS

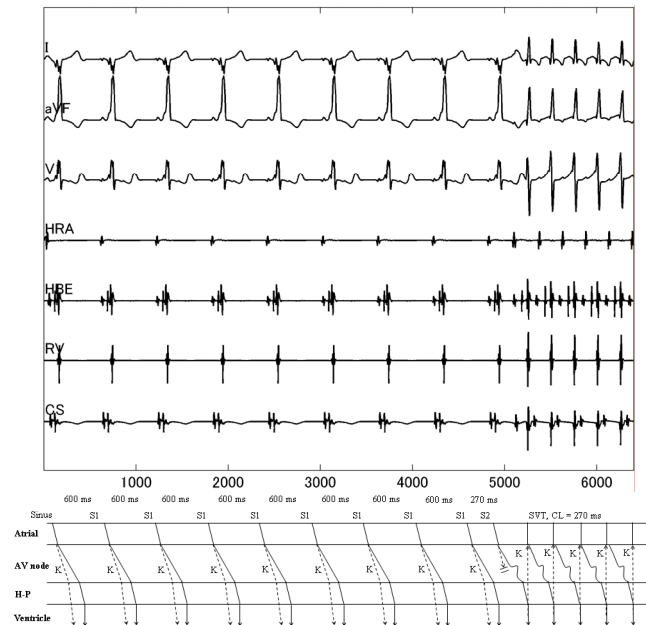


Fig. 2 The atrial extrastimulus pacing, in which S1S2 equals 270 ms after 8 S1 stimuli, is delivered at HRA with the cycle length of 600 ms in the model of WPW syndrome. The SVT is induced after the S2 stimulus. The excitation due to the atrial S2 stimulus is blocked at the Kent bundle. The reentry is formed by the antegrade conduction via the atrioventricular node and the retrograde conduction via the Kent bundle.

By employing the method introduced above, typical pacing protocols in EPS, the basic interval measurement, atrial extrastimulus pacing, ventricular extrastimulus pacing, incremental atrial pacing, and incremental ventricular pacing are reproduced with the model of WPW syndrome (Type A). The tests of the electrophysiological properties of the cardiac tissues such as determination of the refractory period, induction of the Wenckebach rhythms, and induction and termination of supraventricular tachycardias are successfully simulated and the simulation results agree with clinical findings. Figure 2 illustrates the simulated intracardiac electrograms due to atrial extrastimulus pacing. The atrial extrastimulus S2 is delivered to the heart model after a train of 8 atrial stimuli S1 with an interval of 600 ms. As S1S2 270 ms is shorter than the refractory period of the Kent bundle in the antegrade direction, the excitation due to S2 stimuli can only be conducted from the atrium to the ventricle via the AV node, which can be observed in the CS electrograms after the S2 stimuli because the A-V interval becomes much shorter compared with those after S1 stimuli. Then the excitation returns to the atrium from the ventricle via the Kent bundle in

the retrograde direction, and therefore the reentry circuit is formed and the supraventricular tachycardia (SVT) is induced. This phenomenon conforms to the existence of the Kent bundle according to the basic theories and clinical experiences of clinical electrophysiology [1][2]. Similar conclusions can also be obtained by analyzing the intracardiac electrograms simulated with other pacing protocols.

III. CONCLUSION AND FUTURE WORK

This study demonstrates the feasibility and reliability of the computer simulation of EPS with the whole-heart model. This research may show a new direction, the computer simulation of EPS, in the study of electrocardiologic forward problems. This research may also provide a new method for studying, learning, and mastering clinical electrophysiology and catheter ablation. In the future, person-specific whole-heart models and volume conductor models are expected to be constructed from MRI image data for more realistic computer simulation of EPS. The properties of model cells should also be derived from the clinical intracardiac electrogram data measured during EPS.

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