A Network-based Cardiac Electrophysiology Simulator with Realistic Signal Generation and Response to Pacing Maneuvers

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Abstract

Diagnosis and localization of cardiac arrhythmias, especially supraventricular tachycardia (SVT), by inspecting intracardiac signals and performing pacing maneuvers is the core of electrophysiology studies. Acquiring and maintaining complex skill sets can be facilitated by using simulators, allowing the operator to practice in a safe and controlled setting. An electrophysiology simulator should not only display arrhythmias but it has to respond to the user's arbitrary inputs. While, in principle, it is possible to model the heart using a detailed anatomical and cellular model, such a system would be unduly complex and computationally intensive. In this paper, we describe a freely available web-based electrophysiology simulator (http://svtsim.com), which is composed of a visualization/interface unit and a heart model based on a dynamical network. In the network, nodes represent the points of interest, such as the sinus and the atrioventricular nodes, and links model the conduction system and pathways. The dynamics are encoded explicitly in the state machines attached to the nodes and links. Simulated intracardiac signals and surface ECGs are generated from the internal state of the heart model. Reentrant tachycardias, especially various forms of SVT, can emerge in this system in response to the user's actions in the form of pacing maneuvers. Additionally, the resulting arrhythmias respond realistically to various inputs, such as overdrive pacing and delivery of extra stimuli, cardioversion, ablation, and infusion of medications. For nearly a decade, svtsim.com has been used successfully to train electrophysiology practitioners in many institutions. We will present our experience regarding best practices in designing and using electrophysiology simulators for training and testing. We will also discuss the current trends in clinical cardiac electrophysiology and the anticipated next generation electrophysiology simulators.

1. Introduction

Diagnosis and localization of arrhythmias, especially supraventricular tachycardia (SVT), by inspecting intracardiac signals and performing pacing maneuvers is the core of electrophysiology studies (EPS). The ability to perform and interpret such diagnostic maneuvers is a necessary skill for electrophysiologists. While there is obviously no substitute for practicing various maneuvers during a live EPS, logistical and safety considerations preclude a thorough practice in the course of a routine case. As a result, operators may gradually lose the skill to deal with rare arrhythmias.

Acquiring and maintenance of complex skill sets can be facilitated by using simulators, which allow the operator to practice in a safe and controlled setting. For example, flight simulators are commonly used in aviation for pilot training and are considered an integral part of the training programs. More recently, simulators have entered the medical field and are gradually becoming an integrated part of the skill training, and competency assessment [1].

An electrophysiology simulator should not only display arrhythmias but also respond to user's inputs (in the form of arbitrary pacing maneuvers) in a realistic way. A system that only replays recorded arrhythmias with minimal responsiveness is not capable of fulfilling these requirements. To achieve this, the simulator needs an internal *state model*.

While in principle it is possible to model the heart using detailed anatomical and cellular electrophysiological models (e.g., using a diffusion-reaction system and Hodgkin-Huxley style ionic models)[9], most of such models are unduly complex, computationally expensive, and not practical for realtime simulation. However, more recently, there is much interest in detailed simulations [10], especially before ablations to define the target circuit[2].

Fortunately, simpler whole heart models can capture the gross electrophysiological behavior without attention to the details of the underlying cellular physiology and are generally sufficient to reproduce realistic arrhythmia in interactive modes[11]. Some simplified models are based on

the concept of *cellular automata*, which model the heart as a regular grid, where each node of the grid can switch among a finite number of states (e.g., resting, active or refractory) according to few local rules (i.e., rules that depend only on the state of a given node and its immediate neighbors). Historically, Moe's groundbreaking work on computer modeling of atrial fibrillation in the early 1960s was such a model [3].

Nevertheless, cellular automata are not the only possibility. Instead, it is feasible to model the heart as a network (or graph), where nodes are points of electrophysiological interest, such as sinus node, atrioventricular (AV) node, and right ventricle (RV) apex. Nodes are connected by links, which model the conduction system and pathways. Malik et al showed that a ten-element model could simulate heart rhythm and its response to artificial pacing [4]. Similarly, Ahlfeldt et al demonstrated the feasibility of such a model in reproducing arrhythmias [5, 6].

The main advantage of network-based simulation tools is that they conceptualize how clinical electrophysiologists think of the cardiac electrical system. In this paper, we present an online electrophysiology simulator based on the network approach. Clinical concepts such as refractory period, conduction delay, and decremental conduction are explicitly coded into the model, but most arrhythmias (especially reentrant tachycardias) are emergent properties of the model. In the rest of the paper, we present the theory of operation and showcase a few examples.

2. Methods

The simulator software is composed of a core that runs the cardiac model (see below) in realtime, a visualization unit (akin to a simplified clinical electrophysiology system) that plots one simulated surface ECG lead (corresponding to V1) and six intracardiac channels (high right atrial, His position, right ventricular apex and proximal, middle, and distal coronary sinus locations), and a stimulator module that allows the user to perform pacing maneuvers from different sites (high right atrium, right ventricular apex and base, high- and low-output para Hisian). The software is implemented as a web application (Figure 1) and is freely available at "http://www.svtsim.com".

The main components of the network based simulator are:

1. The **model graph** (Figure 2), composed of nodes and links (vertices and edges in the language of Graph theory), that represents the static (topological) view of the heart electrical system. As it was mentioned in the Introduction, nodes correspond to the point of electrophysiological interest and are connected by links simulating the conduction pathways. Links can be either unidirectional or bidirectional.
2. The dynamical behavior of the system is determined by the **state machines** assigned to nodes and links. Each node can be either in the **resting** or **refractory** state. Whenever a **resting** node is excited, by either pacing or conduction from its immediate neighbors, it fires (i.e. stimulates its outgoing links) and changes state to **refractory**. After a dynamic interval (refractory period) is elapsed, the node reverts back to the **resting** state. Links can be in either of **resting**, **waiting**, or **refractory** states. Upon stimulation, a **resting** link enters the **waiting** period for a pre-specified delay interval (conduction time). When the waiting period is over, it fires and changes state to **refractory**.
3. A subset of the nodes pose automaticity and fire at specified intervals. These nodes form **pacemakers**, which initiate an excitation wave and include the sinus node, auto-

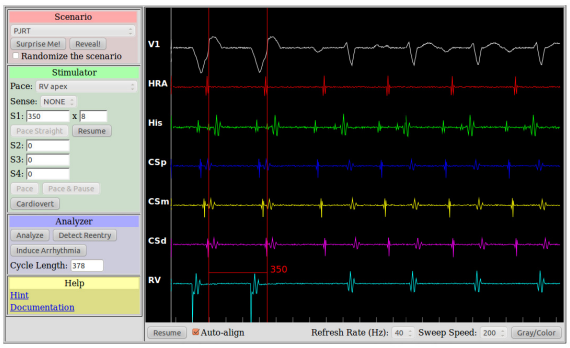

Figure 1. Screen shot of the SVTSIM software (http://www.svtsim.com).

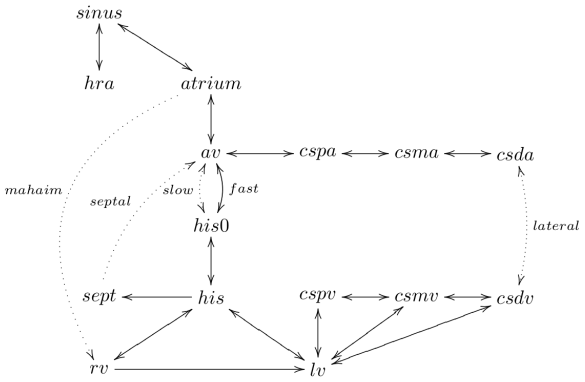

Figure 2. Baseline Graph Dynamical System model. Solid lines show the normal links. Dashed lines represent the pathological links. *av*: atrioventricular node, *csda*: coronary sinus (distal atrial), *csma*: coronary sinus (middle atrial), *cspa*: coronary sinus (proximal atrial), *csdv*: coronary sinus (distal ventricular), *csmv*: coronary sinus (middle ventricular), *cspv*: coronary sinus (proximal ventricular),*hra*: high right atrium, *mahaim*: atriofascicular pathway (Mahaim fiber), *sept*: septal area.

matic foci, and external (user-defined) stimulator.

4. **Electrogram simulator** that converts the network state at any point of time to a set of surface and intracardiac electrograms for visualization.

The flexibility of the system stems from the way timing periods of the nodes and links (e.g., refractory period, conduction delay, and basic cycle length for automatic foci) are dynamically set as a function of the previous cycle length and diastolic interval. This flexibility allows the system to easily emulate phenomena such as decremental conduction, rate-adaption of refractoriness, and paced suppression of automatic foci.

The simulator software also provides ancillary functions to analyze the reentry loop and induce or terminate reentrant arrhythmias. The purpose of *loop analysis* is to determine whether reentry is possible for a given scenario and, if so, to detect the expected cycle length.

3. Results

Abnormal scenarios are generated by starting from a baseline scenario (normal sinus rhythm) and adding or modifying links (dashed lines in Figure 2). Table 1 lists a subset of currently available arrhythmias and their mode of simulation.

Table 1. Different available arrhythmias in SVTSIM and their mode of simulation.

Arrhythmia	Mode
Sick Sinus Syndrome	auto + block
Atrioventricular Block	block
Atrial Tachycardia	auto
Junctional Tachycardia	auto
Atrial Flutter	reentry
AVNRT	reentry
Manifest Accessory Pathways	reentry
Concealed Accessory Pathways	reentry
Atriofascicular Tachycardia	reentry
PJRT	reentry
Ventricular Tachycardia	reentry

For example, the addition of a slow atrioventricular (AV) nodal pathway parallel to the fast pathway creates the atrioventricular nodal reentry (AVNRT) scenario. Similarly, the addition of a lateral accessory pathway (AP) between the distal coronary sinus (CS) and the ventricle generates a model for atrioventricular reciprocating tachycardia (AVRT). Some other implemented scenarios similarly include persistent junctional reciprocating tachycardia (PJRT), atriofascicular pathway (Mahaim fiber), and septal AP.

Non-reentrant tachycardias (atrial or junctional) are emulated by adding an automatic node with stochastic properties, for which the probability of firing is inversely proportional to the previous cycle length.

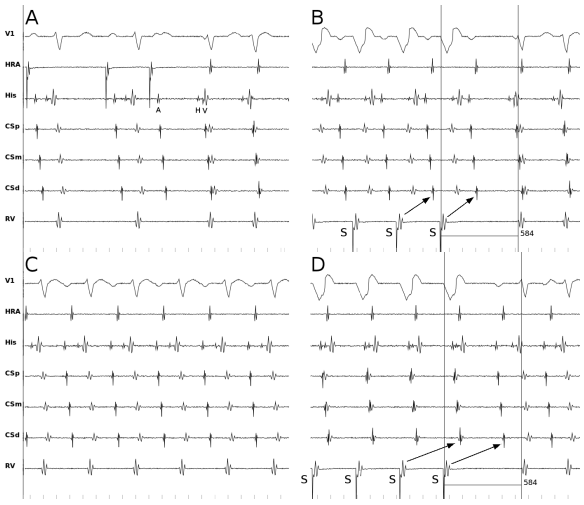

Figure 3. Simulated surface and intracardiac signals in the **AVNRT** scenario. **(A)** Delivering a premature stimulus at coupling interval of 330 ms blocks in the fast pathway, conducts down the slow pathway, and initiates typical AVNRT at a cycle length of 350 ms. Note the near simultaneous activation of atria and ventricles. **(B)** Ventricular overdrive pacing at a cycle length of 330 ms entrains the tachycardia. Note the VAV response, long PPI (134=584-350 ms), and $\Delta VA > 85$ ms, all consistent with typical AVNRT. **(C)** Atypical AVNRT in the same model. **(D)** Ventricular overdrive pacing entrains the tachycardia with a pseudo VAAV response due to long VA conduction. Arrows connects the ventricular paced beats to the corresponding atrial complexes.

In this section, we review an example of an arrhythmia (AVNRT) in detail. We invite the interested reader to supplement the discussion of each arrhythmia by running the simulator at "http://www.svtsim.com".

The addition of a slow pathway to the baseline model creates the substrate for AVNRT. Modification of the slow pathway refractoriness makes reentry possible. Now, a timely atrial extra-stimulus blocks in the fast pathway and initiates reentry (Figure 3A). Ventricular overdrive pacing entrains the reentry with a VAV response (Figure 3B), long post-pacing interval (PPI), and an increase in the VA timing ($\Delta VA > 85$ ms), all consistent with typical AVNRT (slow-fast) [7, 8, 12]. On the other hand, delivery of ventricular extra-stimuli to the same model initiates atypical AVNRT (fast-slow) with prolonged VA interval. Ventricular overdrive pacing again entrains the reentry with a long PPI and a pseudo VAAV response (Figure 3C and D).

4. Conclusions

In this paper, we present an arrhythmia simulator based on a network-based heart model. The simulator successfully reproduces many reentrant and some automatic arrhythmia and exhibits realistic responses to various pacing maneuvers. For nearly a decade, SVTSIM has been used successfully to train electrophysiology practitioners (both clinicians and technologists) in many institutions worldwide.

We believe that the reason such a simple and minimalistic system (20 nodes and 25 links for the baseline sinus rhythm scenario) is capable of reproducing many observed electrophysiological phenomena is the paucity of information available to an operator during a clinical electrophysiology study. An electrophysiologist *sees* the heart through the signals recorded by few strategically placed catheters. As a result, the clinician uses a conceptual model of the cardiac electrical system based on properties such as refractory period, conduction time, decremental conduction, and automatic cycle length, which are captured by the topology of the model graph and its attached state machines. In addition, even given a small number of nodes, say n, one can generate a huge number of possible networks ($2^{n(n-1)}$, for example, for $n = 20$, the number of possible networks is $\approx 10^{117}$).

The primary application of the system is as a training tool. It can be useful for training clinical electrophysiologists and technologists, especially in providing a platform to practice pacing maneuvers for rare or unusual arrhythmias. In this role, the simulator can fill the gap between formal curricular learning and patient care activities and make the whole process safer and more efficient.

Similarly, by presenting an unknown scenario, it helps assessing and evaluating diagnostic skills in a more realistic manner than is possible in a static examination.

The simulator is also a useful research tool. For example, it can be used as a testbed to refine existing pacing maneuvers and test and optimize new ones.

The main limitation of the system is that its behavior is not always realistic or even necessarily clinically possible. In particular, considering that reentry is emergent and is not explicitly defined, there is the possibility of introducing unplanned arrhythmias after any adjustment is made to the underlying model. Some of these arrhythmias could have a clinical counterpart and be of interest on their own, but some may be non-physiological and need to be detected and excluded by extensive testing. The loop analysis routines discussed in the Methods section are helpful in this regard.

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