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Interactive training system for interventional electrocardiology procedures

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ABSTRACT

Recent progress in cardiac catheterization and devices has allowed the development of new therapies for severe cardiac diseases like arrhythmias and heart failure. The skills required for such interventions are very challenging to learn, and are typically acquired over several years. Virtual reality simulators may reduce this burden by allowing trainees to practice such procedures without risk to patients. In this paper, we propose the first training system dedicated to cardiac electrophysiology, including pacing and ablation procedures. Our framework involves the simulation of a catheter navigation that reproduces issues intrinsic to intra-cardiac catheterization, and a graphics processing unit (GPU)-based electrophysiological model. A multithreading approach is proposed to compute both physical simulations (navigation and electrophysiology) asynchronously. With this method, we reach computational performances that account for user interactions in real-time. Based on a scenario of cardiac arrhythmia, we demonstrate the ability of the user-guided simulator to navigate inside vessels and cardiac cavities with a catheter and to reproduce an ablation procedure involving: extra-cellular potential measurements, endocardial surface reconstruction, electrophysiology mapping, radio-frequency (RF) ablation, as well as electrical stimulation. A clinical evaluation assessing the different aspects of the simulation is presented. This works is a step towards computerized medical learning curriculum.

1. Introduction

Cardiac arrhythmia and heart failure are life-threatening pathologies. Cardiac arrhythmia is an abnormal electrical activity in the myocardium (heart muscle), whereas heart failure occurs when the heart can not pump sufficiently to meet the need of the body. Since cardiac electrophysiology induces the contraction of the cardiac muscle, any abnormal electrical stimulation pattern may lead to abnormal contractions of the heart potentially causing heart failure. Depending on the pathology, different therapies are pursued. RF ablation is performed for ventricular tachycardia, whereas Cardiac Resynchronization Therapy (CRT) is preferred in case of severe heart failure. In this paper, we only consider ventricular extrasystole, i.e. ventricular tachycardia caused by ectopic foci. An ectopic focus is an abnormal pacemaker area (outside of the sinoatrial node) that initiates abnormal self-generated beats. Such pathologies can occur due to changes in the heart structure subsequent to a coronary artery disease or as chronic consequences of hypertension, diabetes or cardiomyopathy, as stated in Maron et al. (2006).

The use of minimally invasive techniques is now widespread in many medical fields. Cardiology is no exception. However, less invasive interventions often implies more complex pathways to reach the region of interest. Considering ectopic foci located inside the right ventricle (RV), the procedure first consists of inserting catheters in the femoral vein which allows direct access to the right atrium (RA). Under fluoroscopic imaging, endovascular navigation not only requires an in-depth knowledge of the vascular system but also good hand-eye coordination. Once the RA is reached, the catheter must be skillfully handled in order to access the RV through the tricuspid valve. The electrophysiologist must then perform a 3D reconstruction of the RV endocardial surface. Afterwards, the recording of the electrical activity is performed by acquiring a map of activation times. The ectopic focus includes an excitable group of cells initiating a premature (ectopic) heart beat with a specific electrical pattern. Ectopic beats often appear sporadically and several steps are required to define the exact location

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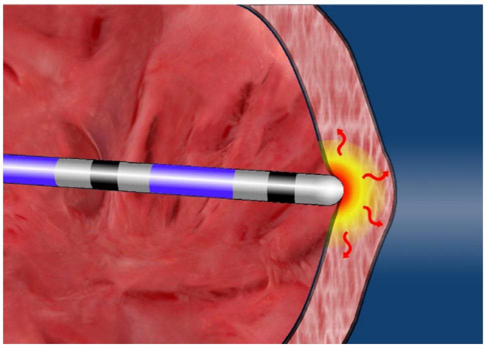

Fig. 1. RF ablation: the catheter heats the endocardial surface to damage the tissues responsible for the pathology.

of the pathological cells. Latest electrophysiology mapping systems are able to automatically detect an ectopic pattern from the analysis of the body surface ECG. As soon as an ectopic beat occurs, the system computes and maps the local activation time on the 3D reconstructed endocardial surface. By scanning the entire cavity, the pathological area can be localized and ablated since the ectopic focus corresponds to the region with the earliest activation time. As illustrated in Fig. 1, RF ablation consists in heating the ectopic focus that leads to its cellular death, thus suppressing the related abnormal beats. RF ablation is frequently preferred to other ablation techniques (high intensity focused ultrasounds, cryotherapy) for cardiac arrhythmia, but the success rate of the procedure remains unsatisfactory: between 50 and 90 % of success, whereas the rate of late recurrence amounts to 20 up to 40 %. According to Aliot et al. (2009), the long-term success rates of RF ablation in the context of scar-related VT even falls between 30 and 60 %. In their paper, authors point out a lack of clinical consensus on the optimum RF ablation strategy, which could explain these unstable success rates.

Until now, residents in cardiology train on patients by separately learning each step of the procedure under the supervision of a senior cardiologist. In order to shorten the training period and to allow a virtual training on complex patient cases, we propose a training system for interventional cardiology based on the simulation of electrophysiology.

Specifications. First, an endovascular catheterization must be provided in the training so that cardiology interns practice navigation in minimally invasive conditions. Then, the biophysical simulation has to reproduce the cardiac electrophysiology as realistically as possible. The trainee can then interact with the simulated electrophysiology, i.e. analyzing the extra-cellular potentials, mapping activation times on the reconstructed endocardium and ablating the arrhythmia. Using our simulation framework for virtual training aims to achieve accurate and fast computations of both navigation and electrophysiology. In this computation, spatial and temporal discretizations must be sufficiently small to reliably reproduce the effect of an ectopic focus, whereas computational efficiency is key to ensure interactivity while navigating inside the blood vessels or interacting with the cardiac electrophysiology (e.g. intra-cardiac measurements, RF ablation or electrical stimulation). To make this framework even more immersive, the simulation environment has to mimic the environment of the operating room.

Previous work. Previous research projects have led to training simulators in cardiology, as Dawson et al. (2000). The most recent simulator is proposed by Chiang et al. (2013) and focuses on intra-ventricular navigation. The contribution of this work consists in virtually reproducing the conditions for the slip and non-slip interaction of the catheter. Authors present a qualitative analysis of the catheterization training using experimental data on a porcine left ventricle, as well as a user evaluation. Few training systems succeeded to be commercialized such as Cathi from Siemens (2006), VIST from Mentice (2012), Simantha from SimSuite (Corporation, 2013), CathLabVR from CAE (HealthCare, 2013) and Angio Mentor from Simbionix (2012). These simulators mostly focus on endovascular navigation and include pre-recorded electrocardiograms (ECG), but none of these simulators includes a biophysical modeling of the cardiac electrophysiology, or models the interaction between a catheter and cardiac electrophysiology.

Simulating the human cardiac electrophysiology is a wide field of research. However, only recent work by Talbot et al. (2013a); Rapaka et al. (2012); Bartocci et al. (2011) investigate high performance computing applied to cardiac electrophysiology in order to achieve quasi real-time simulations. Therefore, coupling both a simulation of endovascular navigation and a model of cardiac electrophysiology while keeping performances close to real-time is extremely challenging.

Proposed framework. We present a training system dedicated to interventional electrocardiology procedures that combines endovascular catheterization with a biophysical modeling of cardiac electrophysiology. The proposed endovascular navigation takes place inside a beating heart model using a steerable catheter model. A phenomenological model of cardiac electrophysiology based on a GPU implementation allows reaching a high level of interactivity. Using a multithreading approach, we couple cardiac electrophysiology and catheter navigation simulations, both running separately in real-time but at different time steps. This contribution enables the simulation to meet the requirements related to training systems in terms of computational efficiency and accuracy. With this framework, the user can interactively visualize bipolar potentials, reconstruct the endocardial surface while mapping activation times, and perform RF ablation or electrical stimulation in real-time. Inspired by the setup of a catheterization laboratory (or cath lab, see Fig. 2(a)), our framework reproduces fluoroscopic images, and intra-cardiac ECG plots. As shown in Fig. 2(b), it also interfaces with a tracking device from Mentice (2012).

This paper is written according to the structure of the training simulator displayed in Fig. 3. First, we focus on the catheter navigation in the scope of electrocardiology, i.e. with a moving environment. Second, the computational model chosen to simulate cardiac electrophysiology is presented. Third, we describe how the navigation and electrophysiology simulation are integrated and interfaced in our framework. Finally, a performance analysis and a clinical evaluation are conducted based on a synthetic case of ventricular extrasystole.

2. Catheter navigation in cardiology

The simulator is developed using SOFA[1] (Faure et al., 2012) and reproduces an intervention aimed at ablating an ectopic focus located in the RV. In this section, we first provide the background on the catheter navigation model. Then, we present a beating heart model extracted from cine magnetic resonance imaging (MRI) data and its coupling with the collision response process. The section ends with the presentation of our steerable catheter model.

[1] SOFA is an open source framework for interactive numerical simulations in medicine. More information about SOFA can be found at http://www.sofa-framework.org.