Modeling Supraventricular Tachycardia Using Dynamic Computer-Generated Left Atrium

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ABSTRACT

Supraventricular Tachycardia (SVT) is when the heart's upper chambers beat either too quickly or out of rhythm with the heart's lower chambers. This out-of-step heart beating is a leading cause of strokes, heart attacks, and heart failure. The most successful treatment for SVT is catheter ablation, a process where an electrophysiologist (EP) maps the heart to find areas with abnormal electrical activity. The EP then runs a catheter into the heart to burn the abnormal area, blocking the electrical signals. Much is not known about what triggers SVT and where to place scar tissue for optimal patient outcomes. We have produced a dynamic model of the right atrium accelerated on NVIDIA GPUs. An interface allows researchers to insert ectopic signals into the simulated atria and ablate sections of the atria allowing them to rapidly gain insight into what causes SVTs and how to terminate them.

CCS CONCEPTS

• **Applied Computing → Life and medical sciences → Health care information systems; Systems biology;**

KEYWORDS

health informatics; dynamic; electrophysiology; modeling, tachycardia; heart disease

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1 INTRODUCTION

The leading cause of death globally is heart disease followed by strokes. Supraventricular Tachycardia (SVT), though not in itself deadly, is a leading cause of strokes, heart attacks, and heart failure. Therefore, one could argue that SVT is indirectly a leading global killer [1-7]. SVT is a term that encompasses all events where the atria beat too rapidly or are out of sync with the ventricles, this includes atrial fibrillation (AF), atrial flutter, and a multitude of other atrial tachycardias [3, 4, 8-14]. This out-of-sync beating between the atria and the ventricles can cause blood to pool in the atria creating clots that can then travel to the brain or coronary arteries resulting in stroke or heart attack [3, 4, 8]. SVT events also greatly reduce the stroke volume of the heart and if they persist for extended periods of time they can cause a permanent reduction in ejection fraction, possibly resulting in congestive heart failure [15].

SVT events occur when rogue electrical impulses interfere with the normal sinus rhythm of the heart. In a normally functioning heart, the sinus node acts as an orchestra conductor and methodically sends out a periodic electrical impulse. This electrical pulse starts a chain reaction throughout the heart causing the muscles of the heart (myocardium) to rhythmically contract to produce an orchestrated beat. Rogue electrical impulses can cause chain reactions to occur at the wrong place and at the wrong time, disrupting the sinus rhythm [2]. This can cause the atria to flutter, beat out of step with the ventricles, or have a myriad of other undesirable outcomes. The beating heart is a three-dimensional nonlinear dynamical system that is sensitive to initial conditions. Hence, SVT events can produce chaotic outcomes that are impossible to predict analytically and must be simulated numerically on high-performance computers.

1.1 Traditional Procedures

SVT events can sometimes be successfully controlled with drugs, but the patient can build up a tolerance and doses must be increased over time. The downside to drug treatment for stopping SVT is that these drugs can be extremely hard on the liver and can lead to liver failure. Hence, although much more invasive, catheter ablation has proven to be the method of choice when treating SVTs [6, 16, 17-19].

1.2 Problem Statement

Radiofrequency catheter ablation and three-dimensional mapping techniques have greatly improved over the last ten years, allowing doctors to perform procedures on beating hearts. But the beating heart can be a chaotic system, making it extremely difficult to predict precisely what outcome will result from changes to the system such as those introduced by ablation lesions [3, 4]. Hence, most ablations are limited to educated guesses that doctors hope will result in positive outcomes. Educated guesses are refined and improved through trial and error [6, 20-22]. Trial and error on living patients have obvious downsides and limitations. What is needed is a way to test out ideas that are not so deadly, costly, and time-consuming. Doctors and researchers need a computer-generated dynamical model of the heart that they can perform experiments on. We have created such a model that will beat in real-time so doctors and researchers can study SVT events and how to remove them to return the heart to sinus rhythm.

2 MODELING

2.1 Proof of Concept

First, a one-dimensional model allowed visualization of the flow of action potential through a single accurately scaled bundle of cardiac muscles [10-12]. Moving up in dimension, a two-dimensional model was created to reproduce various known tachycardia types that occur throughout the heart and pulmonary veins [6, 16, 18, 19, 23]. In a two-dimensional loop, we were able to demonstrate the active effects of ablation. Using this, atrioventricular nodal reentry tachycardia (AVNRT) evolves naturally, which we then could eliminate through ablation. Having shown this, we advanced to a three-dimensional model. In this dimension, we were able to create branching structures to accurately simulate cardiac muscle tissue. With the right initial conditions, we invoked the evolution of several atrial tachycardias. At this point, the nodal count significantly increased, and we transitioned to parallel processing.

2.2 Model Verification

Patients with AF have the majority of malfunctions in the left atrium, hence this is the area our work focuses on [6, 8, 15, 18, 19, 24-26]. To substantiate the model, common symptoms that are known to cause atrial flutter were introduced. We managed to produce roof-dependent atrial flutter and mitral flutter accurately. These induced arrhythmias were eliminated with simulated ablations. Next, we moved on to AF. AF is the most prevalent cardiac arrhythmia and the least understood. It is characterized by chaotic electrical signals that cause an erratic beat in the atria [3, 4, 8-14, 24]. We introduced conditions in the model that would bring about AF which closely matched what is seen in clinical cases [2-4, 6, 8, 24, 27].

2.3 Patient-Specific

The ultimate goal of this project is to produce patient-specific models that EPs can use to assess procedures before going into surgery. We have been able to produce models given sets of assets and muscle attributes [28]. We are currently working to get clinical data to refine our model. We hope that this will enable us to come up with new techniques to benefit patients with extreme cases.

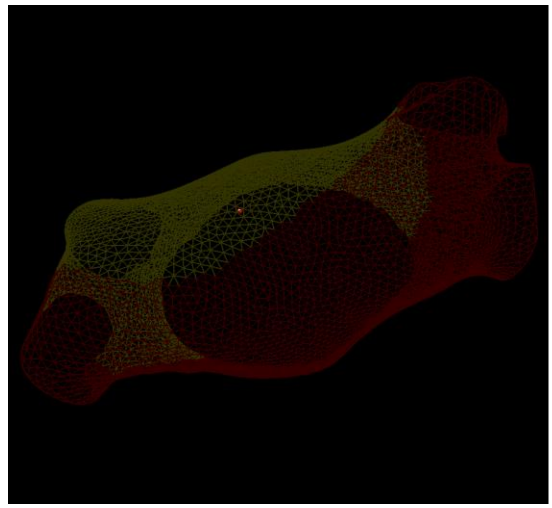

Figure 1: Screenshot of the left atrium entering a beat and processing a contraction.

3 METHODS

The code was written in C/C++ and CUDA. The simulations were accelerated on CUDA-enabled NVIDIA GPUs. OpenGL was used to visualize the simulations. The model assets were generated with Blender using Blender's python package BPY. Nsight Systems were used to help extend CUDA acceleration techniques.

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