# Investigating the Impact of Parameter Selection on Reentry Characteristics in a 3D Slab Simulation

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## Abstract

*Cardiac computational modeling has been extensively employed to investigate the mechanisms underlying various cardiac arrhythmias. A three-dimensional (3D) tissue model (4 cm × 4 cm × 0.04 cm) was created using a tetrahedral mesh to study tissue-scale properties. The single-cell model published by Tomek et al. was integrated into the 3D tissue model, and simulations were conducted using openCARP. The parameter selection included two discretization methods (uniform and adaptive tetrahedral meshes), timesteps ranging from 5 to 20 μs, and three initialization state variable generation methods: default model states (default), pacing the single-cell model 10 times with a basic cycle length of 600 ms (sv_init), and pre-pacing the 3D tissue model for 10 cycles with default model states (pre-pace). The results indicate that reentry characteristics in the 3D slab simulation were significantly influenced by different parameter selections. Careful selection of appropriate parameters in cardiac modeling is crucial for accurately interpreting the mechanisms of arrhythmia.*

## 1. Introduction

It is widely believed that cardiac modeling and simulation can help explain phenomena measured in a range of experiments or clinical measures and reveal the underlying mechanisms of various heart diseases [1]. In recent years, personalized heart modeling has been used in the research of various fatal arrhythmias and their non-invasive treatment [2]. Tomek et al. [3] recently developed a model (named the Tomek model) that can reproduce key depolarization, repolarization, and calcium dynamics properties of healthy ventricular myocytes [4]. This model has been widely used in one-dimensional (1D) to three-dimensional (3D) simulations [5].

Many parameters have a certain influence on the reentry characteristics in 3D simulations. Cao et al. have studied the difference between different types of meshes with varying mesh resolutions, finding that the relative difference in activation time was significantly greater for uniform tetrahedral meshes compared to adaptive tetrahedral meshes [6]. The developers of the open-source software openCARP [7] have introduced three methods for assigning initial values. The first is default model states (default), which means that all single cells are initialized with the default state of the single-cell model hard-coded in openCARP. The second is to initialize all cells using the stored cell model state (sv_init). The last is to initialize the cells with a model state taken instantaneously at different times based on a priori known activation times (pre-pace).

A 3D tissue model was created using a tetrahedral mesh to study tissue-scale properties. Parameter selection consists of two discretization methods, different timesteps, and three initialization state variable generation methods. Different parameter choices are used to analyze the reentry characteristics. The experimental results show that the conduction speed of the adaptive tetrahedral mesh model was faster, and the reentry trajectory differed with varying timesteps. Additionally, the conduction speed was fastest in models with default state values.

## 2. Methods

A 3D tissue model was created using a tetrahedral mesh to study tissue-scale properties. The size of the tissue model was 4 cm × 4 cm × 0.04 cm, and the isotropic conductivity was set to 0.008 S/m. A first thin layer of stimulation with an intensity of 60 μA/cm$^2$ was applied to the left side of the tissue model, and after a certain period, another stimulation with an intensity of 30 μA/cm$^2$ was added to the lower half of the tissue model. The single-cell model published by Tomek et al. was integrated into the 3D tissue model and simulated using

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openCARP [7] (https://opencarp.org/).

## 2.1. Influence of grids generated by different discretization methods

We compared the simulation of the Tomek model on meshes generated by different discretization methods (uniform tetrahedral mesh and adaptive tetrahedral mesh). The average mesh resolution of the uniform tetrahedral mesh model was 119.926 ± 20.6958 μm, and that of the adaptive tetrahedral mesh model was 116.492 ± 28.5885 μm. The initial valuation method used in the simulation of both meshes was sv_init, and the timestep was 10 μs. The second stimulus started at 430 ms, and the model ran for 10 seconds.

## 2.2. Influence of different initialization state variable generation methods

We compared the two-dimensional (2D) simulation results of the Tomek model using the adaptive tetrahedral grid under three initial evaluation methods: default model state (default), pacing the single-cell model 10 times with a basic cycle length of 600 ms (sv_init), and pre-pacing the 3D tissue model for 10 cycles with the default model state (pre-pace). The timestep was 10 μs, and the time interval between the second stimulus and the first stimulus was 360 ms. The initial assignment methods, which were default and sv_init, took 5 seconds to run, while the pre-pace method took 10 seconds to run. sv_init was a 2D tissue model that initialized all cells with the same membrane potential at the end of the single-cell simulation, and the state variables were instantly saved to a file at a specified time. In the pre-pace method, cells were initialized instantaneously with membrane potential and other state variables at different times. The stimulus intensity in the pre-pace method was 60 μA/cm$^2$.

## 2.3. Influence of different timesteps

We compared the results of the Tomek model using an adaptive tetrahedral mesh on the openCARP experimental platform with timesteps of 5, 10, 15, and 20 μs, respectively. The initial assignment method was sv_init, the start time of the second stimulus was 360 ms, and the model ran for a total of 5 seconds.

# 3. Results

## 3.1. Influence of grids generated by different discretization methods

We compared the 2D simulation of the Tomek model on uniform tetrahedral mesh and adaptive tetrahedral mesh.

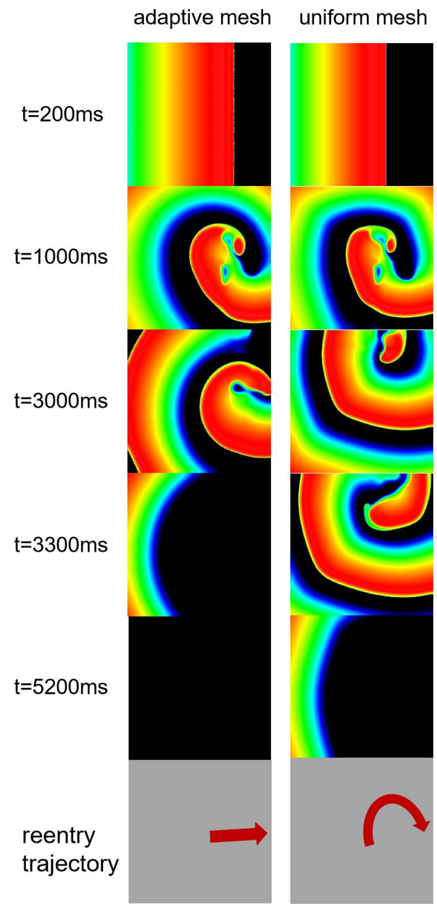


Figure 1. 2D reentry results of the Tomek model on uniform tetrahedral mesh and adaptive tetrahedral mesh.

Figure 1 shows the 2D simulation results of the Tomek model on the uniform tetrahedral mesh and the adaptive tetrahedral mesh. The first row represents the conduction image when the second stimulus was not applied after the first stimulus. It can be observed that the conduction speed of the adaptive tetrahedral mesh was faster, indicating better mesh quality. As the simulation progressed, the difference between the two meshes gradually increased, with the reentry of the adaptive tetrahedral mesh disappearing first and the reentry trajectories differing between the two meshes. Moreover, the reentry pattern of the adaptive tetrahedral mesh was more circular compared to the uniform tetrahedral mesh, further indicating the superior quality of the adaptive tetrahedral mesh.

## 3.2. Influence of different initialization state variable generation methods

We compared the 2D simulation results of the Tomek model using an adaptive tetrahedral mesh under three initial valuation methods: default, sv_init, and pre-pace.

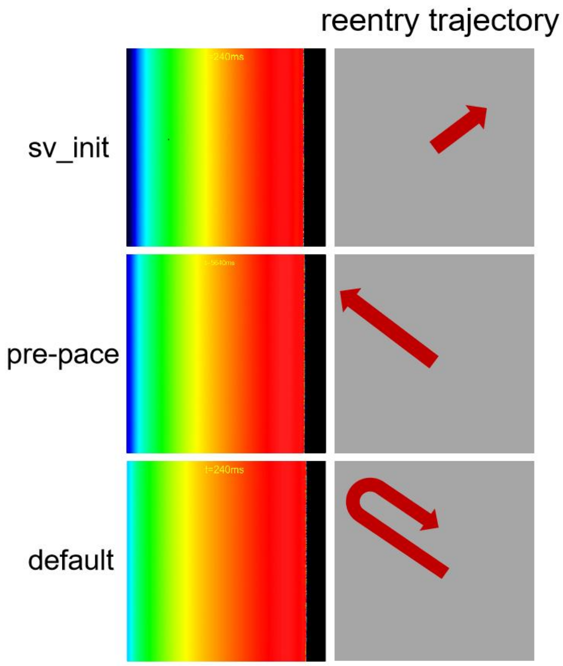


Figure 2. 2D reentry results of the Tomek model under three initial valuation methods, including the conduction images of the first stimulus and the reentry trajectory.

Figure 2 shows the 2D simulation results of the Tomek model under three initial valuation methods. The first column represents the conduction image after the first stimulus was applied but before the second stimulus. Based on the wavefront positions of the three methods, it can be observed that the default initial assignment method resulted in the fastest conduction speed, followed by the pre-pace method, with the sv_init method exhibiting the slowest conduction speed. The second column in Figure 2 illustrates the reentry center moving path, i.e., the trajectory of the reentry. It is evident that the 2D reentry trajectories under the three initial valuation methods were not identical and exhibited significant differences. Additionally, the sv_init method led to an early termination of the 2D reentry, while the other two methods did not result in early reentry termination during the simulation process.

## 3.3. Influence of different timesteps

We compared the 2D simulation results of the Tomek model with an adaptive tetrahedral mesh and the sv_init method using timesteps of 5, 10, 15, and 20 μs, respectively.

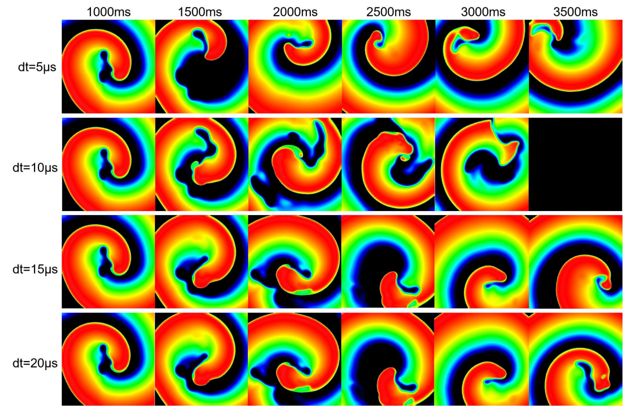


Figure 3. 2D reentry results of the Tomek model under different timesteps, including reentry images at different simulation times.

Figures 3 and 4 present the results of the 2D simulation of the Tomek model under different timesteps. From the reentry images in Figure 3, it can be observed that the 2D reentry generated by the Tomek model exhibited wave fragmentation. Furthermore, the 2D simulation with a timestep of 10 μs terminated prematurely, which might be attributed to the limited grid area, high conduction speed, and boundary conditions. By comparing the 2D reentrant images with adjacent timesteps, it was observed that the images with timesteps of 5 μs and 10 μs began to exhibit noticeable differences at approximately 1300 ms. Similarly, the images with timesteps of 10 μs and 15 μs also started to show significant differences around 1300 ms. Images with timesteps of 15 μs and 20 μs began to display substantial differences at around 3200 ms.

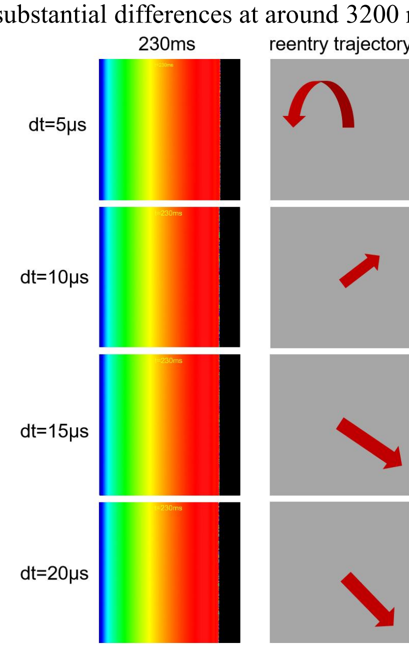


Figure 4. 2D reentry results of the Tomek model under different timesteps, including the conduction images of the first stimulus and the reentry trajectory.

The first column in Figure 4 represents the conduction image after the application of the first stimulus but before the second stimulus. It can be observed that the conduction velocities of 2D simulations with different timesteps varied only slightly. The second column in Figure 4 illustrates the trajectory of the reentry operation. It is evident that the reentry trajectory changes with varying timesteps, but no clear pattern emerges.

## 4. Conclusions

In this study, we employed a tetrahedral mesh to construct a 3D tissue model to investigate the properties of tissue scale under different parameter choices. The parameter selection includes two discrete grid generation methods, three initial valuation methods, and four different timesteps. The experimental results demonstrated that the adaptive tetrahedral mesh model exhibited faster conduction speed and higher mesh quality. Furthermore, the conduction speed was fastest in models with default state values. Additionally, the reentry trajectories varied with different timesteps. These findings indicate that different parameter selections have a significant influence on the reentry characteristics in 3D slab simulations. Careful selection of appropriate parameters in cardiac modeling is crucial for accurately interpreting the mechanisms of arrhythmia.


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