Is it Possible to Stimulate an Isolated Heart in Multiple Directions Using Only Two Pairs of Electrodes?

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Abstract

Ventricular fibrillation (VF) is a life-threatening arrhythmia, and defibrillation is currently the only effective method for reversing it. However, conventional protocols may cause myocardial injury due to the high intensity of the applied electric fields (E). Multidirectional stimulation can reduce E intensity but typically requires one electrode pair per direction. This study explores whether monodirectional stimuli in multiple directions can be generated using only two electrode pairs, as a step toward future multidirectional protocols. Using COMSOL Multiphysics (v5.4), we simulated monodirectional fields of 3 V/cm in five directions (0°, 30°, 45°, 60°, and 90°) on an isolated rat heart. By varying the stimulus amplitude along each axis, we demonstrated directional control using only two electrode pairs. Simulations confirmed accurate field orientation, with a maximum E of 5.5 V/cm—sufficient to stimulate cardiac tissue without causing damage. The results show that this approach offers the potential to optimize defibrillation protocols, enhancing efficacy while minimizing myocardial damage.

1. Introduction

Ventricular fibrillation (VF), characterized by chaotic and asynchronous activation of ventricular cells, is a highly dangerous arrhythmia that leads to cardiocirculatory arrest and death [1], with a survival rate of only about 30% of the pacients [2].

Defibrillation is a procedure capable of reversing VF by applying high-intensity electric fields (E) to the thorax or directly to the heart. However, this method carries the risk of damaging cardiac tissue [3–5], highlighting the need to refine defibrillation protocols to enhance their efficacy.

Multidirectional stimulation (application of stimuli sequentially in multiple directions) has been explored as a means to optimize current defibrillation protocols, typically requiring a separate pair of electrodes for each stimulation direction [6, 7]. However, this approach may not always be viable.

In this study, we investigate the feasibility of stimulating an isolated heart in a stimulation chamber using only two pairs of electrodes, leveraging the superposition principle.

According to this principle, the vector sum of the E generated along each axis results in a resultant electric field E_R, as expressed in Equations (1) and (2):

$$E_R = \sqrt{(E_x)^2 + (E_y)^2} \tag{1}$$

$$\alpha = \arctan\left(\frac{E_y}{E_x}\right) \tag{2}$$

where E_R is the resultant E, E_x and E_y are the linear contributions of the E intensity along each axis, and α is the angle of E_R relative to the x-axis. So, by varying the intensity of E applied to each axis, we could apply the stimulus in different directions, and with different intensities.

To achieve this, we applied monodirectional stimuli in five different directions, based on the superposition principle. This approach aims to enable future multidirectional stimulation within this configuration, with the potential to integrate it into defibrillation protocols, enhancing efficacy while minimizing tissue damage.

2. Methods

In this work, a computational model was developed to emulate a biological experiment in which an isolated rat heart is placed at the center of a stimulation chamber. The model applies monodirectional pulses based on the superposition principle to investigate the feasibility of stimulating the heart in different directions using only two pairs of electrodes.

For this purpose, we used COMSOL Multiphysics (v5.4, Stockholm, Sweden), a reference software for solving or-

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dinary and partial differential equations using the finite element method.

To simulate monodirectional stimulation, a 5 ms voltage pulse was applied to the electrodes. These pulses were generated using a stimulation signal function in MATLAB R2021a (MathWorks, USA) and then imported into COMSOL, where the simulation was carried out.

2.1. Geometry

The stimulation chamber developed has dimensions of 15 × 15 cm and contains two stimulation electrodes positioned on opposite walls.

The chamber is filled with the electric properties of the Krebs-Henseleit (K-H) solution. The stimulation electrodes are 14 cm wide, with a submerged section of 4 cm. This configuration ensures an uniform E distribution within the chamber, which can be determined using Equation 3 [8]:

$$E = \pm \frac{I}{\sigma h l} \tag{3}$$

where E is the electric field, I is the stimulation current, h is the height of the K-H solution, l is the electrode width, and σ is the solution conductivity inside the chamber.

The heart was modeled by combining two geometries: a half-sphere and a half-ellipsoid, designed to approximate the shape of a murine heart. The sphere has a radius of $R = 1$ cm, while the ellipsoid has dimensions of $a = 2$ cm, $b = 1$ cm, and $c = 1$ cm. The total heart surface area was calculated as $A = 17.02$ cm^2.

Figure 1 illustrates the stimulation chamber with the isolated rat heart positioned at its center, oriented at 90° to the x-axis and immersed in a medium with the properties of the K-H solution, which has a conductivity of 1.5 S/m [9] and a relative permittivity of 76 [10]. The heart itself has a conductivity of 0.16 S/m and a relative permittivity of 94×10^6 [11].

2.2. Simulation Parameters

The numerical simulation was conducted to assess the distribution of E within the stimulation chamber, with no regard for the thermal analysis of the model. In Table 1 we can see the parameters used in this model.

Table 1. Simulation Parameters

Parameter [unit]	Value
Solution electrical conductivity [S/m]	1.5
Solution relative permittivity	76
Heart electrical conductivity [S/m]	0.16
Heart relative permittivity	$94 \cdot 10^6$

2.3. Analysis of the E in the isolated heart

Monodirectional pulses with a duration of 5 ms were applied in the 0°, 30°, 45°, 60°, and 90° directions to observe variations in stimulus direction within the heart. The applied E was consistently 3 V/cm, sufficient to stimulate the heart [12].

Figure 2 illustrates the pulses along x- and y-axes when an E of 3 V/cm is applied at a 30° stimulus direction.

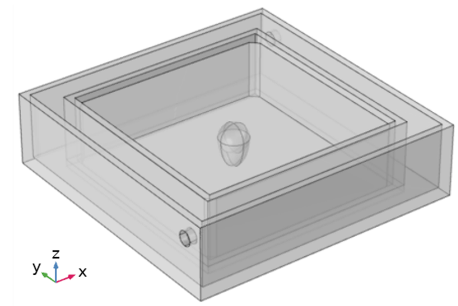

Figure 1. Stimulation chamber with the isolated heart centralized.

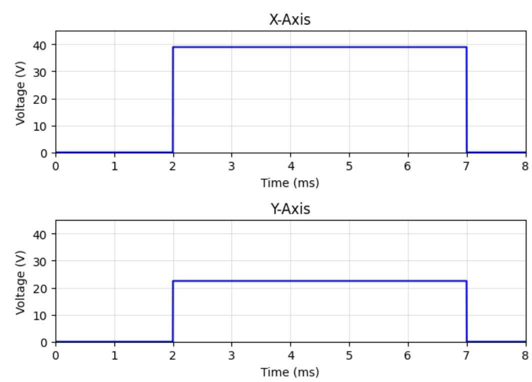

Figure 2. Electric field of 3 V/cm when the stimulus application direction is 30°.

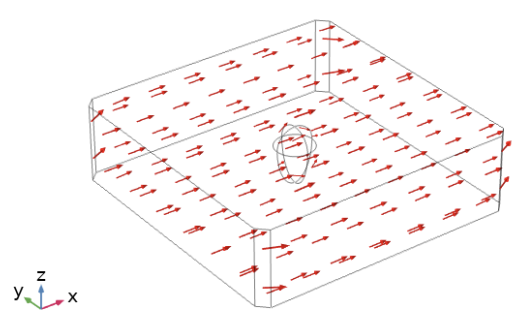

Figure 3. E lines when applying a stimulus in the 0° direction, with the heart positioned at 90° to the x-axis.

3. Results

Figure 3 illustrates the E lines when a stimulus is applied in the 0° direction, with the heart positioned at 90° to the x-axis. Figure 4 provides a top-down view of the E lines within the heart, demonstrating how the E distribution adjusts based on the applied stimulus and heart model.

Figure 5 depicts the variation of E within the heart when an E of 3 V/cm is applied in the 0° direction. We can see that the maximum E point is 5.41 V/cm, which is insufficient to damage heart cells [13].

Figure 6 shows the variation of E within the heart for different stimulus directions: 30° (Figure 6-A), 45° (Figure 6-B), 60° (Figure 6-C), and 90° (Figure 6-D). The variation in E direction is clearly visible, as indicated by the regions of higher intensity (red areas). When measuring the applied directions, they were exactly as intended (0°, 30°, 45°, 60°, and 90°).

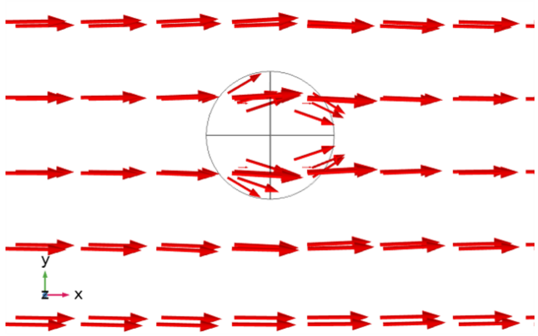

Figure 4. Top-down view of the E lines when applying a stimulus in the 0° direction, with the heart at 90° to the x-axis.

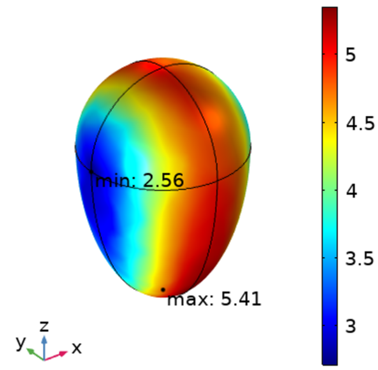

Figure 5. Variation of E in the heart when applying E = 3 V/cm in the 0° direction.

4. Discussion

By applying monodirectional stimuli of 3 V/cm in five different directions, we demonstrated that a configuration using only two pairs of electrodes can generate multiple stimulus directions, eliminating the need for a dedicated electrode pair per direction—a limitation of current protocols [6, 7]. This finding suggests a simplification in electrode placement while maintaining effective stimulation, which could be particularly relevant for reducing hardware complexity in experimental and clinical settings.

Moreover, computational modeling proves to be an indispensable tool in cardiovascular research. By providing a controlled and reproducible environment, it allows researchers to simulate complex physiological responses, optimize experimental designs, and reduce the need for extensive *ex vivo* testing.

Future work should focus on integrating multidirectional stimulation into defibrillation protocols, with particular emphasis on the use of the superposition principle. This would enable the achievement of a multidirectional effect by applying monodirectional stimuli in sequence, enhancing the potential for more effective stimulation techniques. This approach has the potential to improve defibrillation efficacy while minimizing myocardial damage by optimizing the distribution of E with fewer electrode pairs.

5. Conclusions

The analysis of E in an isolated heart validated the feasibility of varying the stimulus direction using only two pairs of electrodes, by applying monodirectional pulses using the superposition principle. This approach simplifies electrode configuration and could enhance defibrillation protocols by improving efficacy and minimizing myocardial damage.

Computational modeling was essential for simulating the heart's response to various stimuli, offering valuable insights without experimental resources. Future work should focus on integrating multidirectional stimulation with the superposition principle into defibrillation protocols, potentially optimizing cardiac stimulation techniques in both research and clinical settings.

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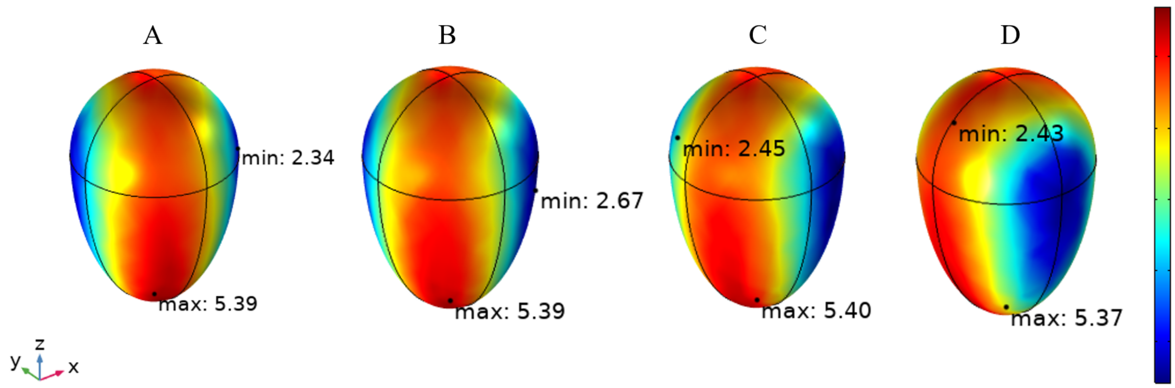

Figure 6. Variation of E in the heart when applying E = 3 V/cm in the 30° (A), 45° (B), 60° (C), and 90° (D) directions.

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