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Effect of Shock Vector Orientation in Modulating and Terminating Rotors – a Simulation Study*

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***Abstract*— The main treatment option for Ventricular Fibrillation (VF), especially in out-of-hospital cardiac arrests (OHCA) is defibrillation. Typically, the survival-to-discharge rates are very poor for OHCA. Existing studies have shown that rotors may be the sources of arrhythmia and ablating them could modulate or terminate VF. However, tracking rotors and ablating them is not a feasible solution in a OHCA scenario. Hence, if the sources (or rotors) can be regionally localized non-invasively and this information can be used to direct the orientation of the shock vectors, it may aid the termination of rotors and defibrillation success. In this work, using computational modeling, we present our initial results on testing the effect of shock vector orientation on modulating (or) terminating rotors. A combination of Sovilj's and Aliev Panfilov's monodomain cardiac models were used in inducing rotors and testing the effect of shock vector magnitude and direction. Based on our simulation results on an average with four experimental trials, a shock vector directed in the perpendicular direction along the axis of the rotor terminated the rotor with 16% lesser magnitude than parallel direction and 38% lesser magnitude than in oblique direction.**

***Clinical Relevance*— A rotor localization dependent defibrillation strategy may aid the defibrillation protocol procedures to improve the survival rates. Based on the four experimental trials, the results indicate shock vectors oriented perpendicular to the axis of the rotors were efficient in modulating or terminating rotors with lower magnitude than other directions.**

I. Introduction

Sudden cardiac deaths (SCD) account for one of the major causes of death worldwide [1]. Of which, out-of-hospital cardiac arrests (OHCA) have very poor survival-to-discharge. Based on a study [2], the survival to hospital discharge of OHCA is less than 10%. A majority of OHCA and eventual SCDs are due to ventricular fibrillation (VF). The heart is basically an electromechanical pump, which in normal conduction, contract and expand by the electrical excitation arising from sinoatrial node. This highly coordinated electrical activation pattern is disturbed during VF causing uncoordinated and rapid muscle contractions leading to poor circulation of blood. Many existing studies have suggested that the VF may be driven by spatiotemporally organized electrical activities called rotors [3,4].

Existing study has shown that tracking these rotors and ablating them can terminate atrial fibrillation in a canine model [5]. In [5], the canine model was subjected to current injection to generate the rotors. A 64-electrode catheter was used to identify the rotors. Ablation was then performed at the rotor locations as well as the non-rotor locations. These ablation therapies can be used in VF as well [6]. In a proof of concept study [7] it has been shown that such ablation approach could reduce the chances of VF induction at the ablated sites. However, these catheter ablation approaches are exclusively applicable only for in-hospital treatment and cannot be applied to OHCA. For an OHCA scenario, defibrillation by electric shocks and pharmacological interventions remain the only current treatment options. The magnitude settings of the defibrillator and orientation of the shock [8] plays a crucial role in reviving a patient from arrhythmia. A low defibrillation magnitude will not terminate the arrhythmia, on the contrary a higher magnitude electric shock can lead to increased pacing thresholds and myocardial damages.

There are several existing works that have presented different optimization approaches in delivering the shocks to increase the survival rates. Some of the recent works propose modification of shock delivery by the use of double sequential external defibrillation (DSED) [9,10] for refractory VF. These clinical studies indicate that DSED is associated with increased rate of VF termination especially in refractory VF [11,12]. There are also works on low energy defibrillation [13] methods in which the defibrillation is achieved by a feedback mechanism and resonant drift pacing. The work [14] discusses how the variation in the pad positions could affect the defibrillation.

While there are many existing experimental and clinical studies in the area of optimizing defibrillation, researchers have also assessed many aspects of defibrillation using the mathematical computational models. The review work by Shibata et. al [15] discusses many of the works on mechanisms of defibrillation. Detailed computational model of defibrillation using realistic models are presented in [16,17]. An MRI based computational model for termination of VF by application of low voltage stimuli, in two separate stages was proposed by Rantner et al. [18]. Use of high frequency AC and low voltage for defibrillation was proposed by Weinberg et al [19]. Optogenetic treatments are also being proposed as a substitute for electrical cardiac therapies, where a mathematical model of light sensitive tissues for defibrillation using optogenetics was presented [20]. Computer models provide the ability to test conceptual ideas by simulating scenarios which are otherwise lethal or resource intensive. Computer modeling can serve as a reference to plan for elaborate experiments. In our work, we present one such

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modeling effort to test the shock vector orientation on terminating rotors. Although our motivation is also in optimizing the shock delivery, we follow a different approach. While tracking rotors (or regional complexity) non-invasively in an OHCA scenario is a challenging problem but there is potential [4], even before that a critical question would be if shock vector orientation plays a role or not in the success of the shock if rotor localization is made available. To this effect, we set out to experiment, if we could align the shock vectors assuming that we know the rotor locations (or regional complexity) already, will this result in an effective shock. Simulations were carried using COMSOL 5.5. The simulations tested the relation of the defibrillation current density levels and the direction of shock with reference to rotor axis, in modulating and terminating rotors.

II. Methods

For carrying out the simulations, we require a computational model that can simulate rotors in the myocardium. The commonly used cardiac mathematical models can be classified into monodomain model and bidomain models [21]. In the monodomain model we assume that the tissues in a cardiac geometry as a continuous single excitable medium defined by the transmembrane potential and recovery variable. In a bidomain model, we consider the tissues as two separate media with intra cellular and extra cellular spaces. As an initial study, to simulate the proposed experiment, we chose the simpler monodomain model.

A. The Computational model

In our model we employed the Aliev – Panfilov's equations to describe the cardiac electrical activity. The monodomain Aliev - Panfilov's equations [22] can be described as

$$\partial\upsilon/\partial\tau = \nabla.(\Lambda\upsilon) - \kappa\upsilon(\upsilon - \alpha)(\upsilon - 1) - \upsilon\nu + I. \quad (1)$$

$$\partial\nu/\partial\tau = (\varepsilon + \mu_1\nu/(\mu_2 + \nu))(-\nu - \kappa\upsilon(\upsilon - \beta - 1). \quad (2)$$

"υ" is the transmembrane potential, "κ" is the excitation rate constant, "ν" is the recovery variable that initiates repolarization, and "α" is the threshold potential, which is the maximum point that differentiates the excitability and the refractory state. The term "Λ" is the diffusion tensor, which represents the anisotropy caused by the fiber architecture in the cardiac models. In our simulation, we have considered the tissues to be isotropic for simplicity and therefor Λ reduces to a scalar quantity. The values for "Λ" for isotropic fiber orientation was obtained based on previous works [23,24]. Clearly, the first set of equations describe how the initiation and depolarization process is occurring and the second set of equations are the factors which control the repolarization parameters. The parameters were adapted from the literature [25].

The term I in (1) is the externally applied stimulus into the cardiac tissues. In our model, we employ this stimulation or the current injection to initiate a rotor on the epicardium. The injected current was a unit rectangular pulse applied to the selected area in the epicardial surface employing a predefined S1-S2 current injection protocol [26].

B. Geometry

In our work we have adapted a geometry from the works based on Sinisa Sovilj [27]. The entire geometry consists of heart model embedded in a torso. The geometry is well defined that the heart model consists of several subdomains. The major domains include all subparts of heart, blood, insulators and torso. The torso as a domain comprises of a cylindrical shape in which the heart geometry is embedded inside as shown in Fig. 1.

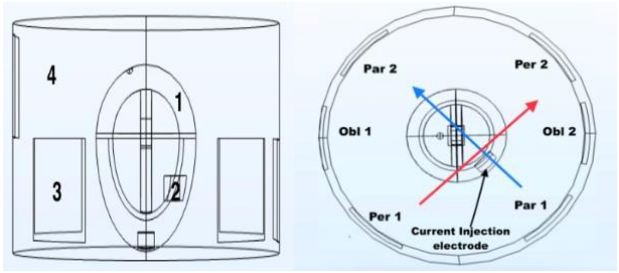

Figure 1. The entire geometry and defibrillation direction. With reference to current injection electrode at left ventricle (for one of the trials), blue arrow represents parallel and red arrow perpendicular directions of shock delivery. Domains: 1- Heart, 2- rotor generation area (for one of the trials), 3- defibrillation pads, 4- Torso

The cylindrical torso ensures that all the pads are at identical distance from the center of the heart model. The injecting electrodes are placed in the outer surface of the epicardium having a dimension of 15x15 millimeters for both pairs and the defibrillating pads were placed along the perpendicular, parallel and oblique directions with the rotor axis. The Fig.1 shows the entire set up of the geometry for one of the trials with rotor being induced in the anterior left ventricle and the two defibrillating pads for each direction being placed along the perpendicular, parallel and oblique directions. With reference to the rotor location in left ventricle, the pads marked as "per1" and "per2" denote the perpendicular direction of the field delivered. The pads "par1" and "par2" are the pad pair along parallel direction and "obl1" and "obl2" are the pads in oblique direction. The parallel and perpendicular pad pairs are placed at same plane while the oblique pad pairs are placed at an angle of +/-15 degrees with respect to other pad pairs. The electrical property of the cardiac model is highly crucial in the activation propagation. These parameters were selected based on adapted values from literature.

C. Rotor generation

The rotors were generated based on one type of functional reentry mechanism [3]. The current was injected into the epicardium at the trailing edge of the relative refractory period at the injecting region using S1S2 protocol. The rotor can be created at any desired location in the geometry. In our simulation the rotors are generated at the lower right ventricle for the first trial. For each successive trials the locations of rotor generation were changed to the left ventricle and then to the posterior sides of the ventricles, and simulations were done. The electrodes were placed at the desired location and a unit rectangular pulse of 2 units duration was injected into the epicardium using the protocol. In our simulation, for all the trials, this rectangular pulse was injected into the epicardium at a time instant of 130 units after the start of the

simulation. The electrode area remains in relative refractory period during this time instant.

D. Defibrillation

The termination of the rotor requires the defibrillation pads to be paced in the torso for the simulations. The pads were positioned so that the analysis was carried out for the defibrillation along, perpendicular, parallel and oblique directions with dimensions covering the area of 60x60 millimeters. The defibrillation pad positions, and size were adapted from the previous work by Dokos [28], in which the pads of the same dimensions were placed in the anterior apex position to achieve the defibrillation in the mathematical model.

III. Results and Discussions

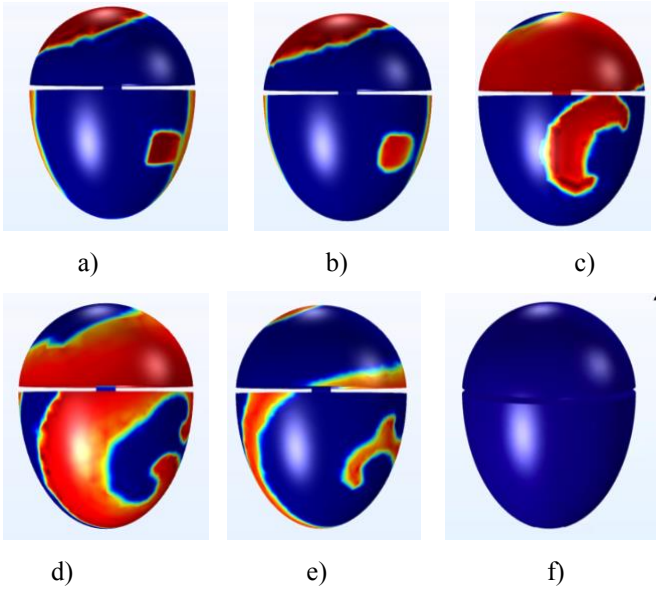

Figure 2. Images depicting the sequence of events: rotor generation, defibrillation, termination and the steady state obtained for one of the trials with parallel defibrillation with I_s magnitude of 5A/m^2

The Fig.2 shows the various events of an experimental trial. In Fig. 2, the subplot (a) shows the repolarization wave passing by the electrode area and the current is being injected into the epicardium using the S1S2 protocol. The subplots (b) and (c) show the preferential path causing the formation of spiral waves. These waveforms then propagate along the preferential paths and both ends later move towards each other as shown in (d). These waves then collide forming new waves. This new wave continues to propagate and once the shock is applied depolarization gradually decays as shown in subplot (e). Due to this decay heart moves back to initial repolarized state as in subplot (f). The Fig.3. demonstrates different current pathways in three directions during the defibrillation. As seen from the subplot (a) with reference to the axis of the rotation of rotors, the current flows in a direction parallel to the axis of the rotor axis. In the subplot (b) the current pathways travel in a direction perpendicular to the rotor axis and the subplot (c) the direction is oblique with reference to rotor axis.

The location for the rotor induction was selected at the right, left, in anterior and posterior locations of the ventricular sections for each of the trials 1,2,3 and 4 respectively. The rotors were induced in these defined locations by the predefined S1-S2 protocol [26]. Fig.4 shows different trials performed and their results. The time of application of defibrillating pulse and the duration of the pulse were held same for all the trials. The different shock magnitudes (in terms of current density) applied is given in the Y axis. The defibrillation current was delivered normally into the torso following the work of Dokos [28].

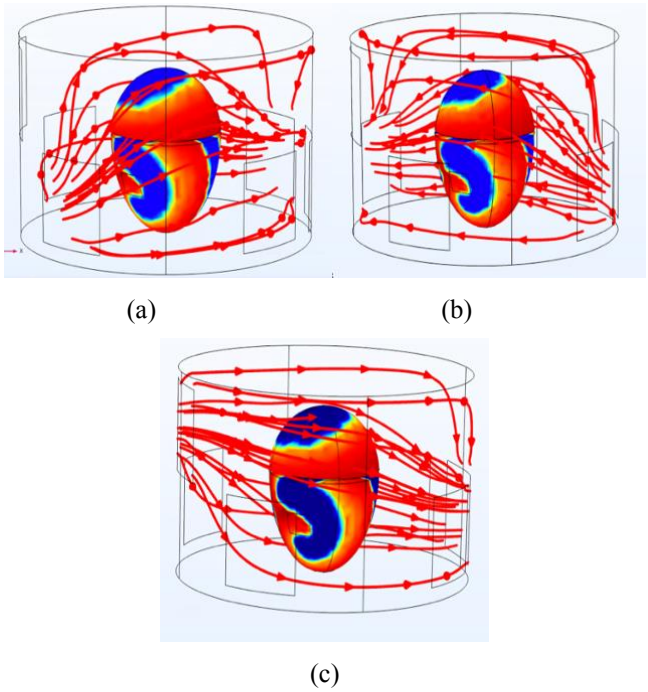

Figure 3. The current density image for one of the trials in a) parallel b) perpendicular c) oblique directions

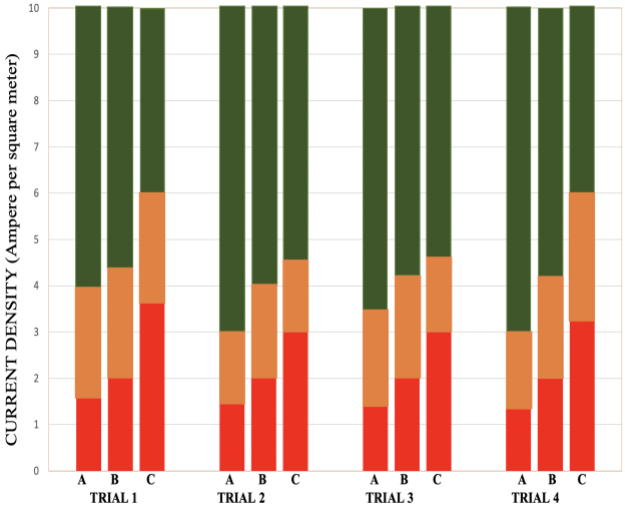

Figure 4. Summary of the results. The Y axis represents current density in A/m^2 and X axis represents four trials corresponding to four different locations. The three bars A, B, C represents the perpendicular, parallel and oblique directions of defibrillation in each trial. The red colour in each bar represents sustainment of rotor, orange represents the rotors being modulated and green colour represents the rotors being terminated.

In Fig.4, the trials 1,2,3,4 represents the rotor located at different locations in the ventricles. The colors in the vertical bars indicate the effect of defibrillation on rotors. The red

color indicates sustained rotor (i.e. no appreciable change in rotor pattern), green indicates the termination of rotors (i.e. cessation of rotor pattern) and orange color indicates modulation of the rotor (i.e. change in rotor pattern but no cessation). As seen from Fig.4. for example, in the trial 2, for the same magnitude of 3 A/m^2, the rotor was terminated for perpendicular direction while it sustained for parallel and oblique direction. Similarly, for the same trial, a magnitude of 4 A/m^2 terminated the rotor in perpendicular and parallel direction while the rotor sustained in oblique direction. Out of the four experimental trials performed at four different locations in the lower ventricle, the perpendicular direction needed an average minimum current density of 3.5 A/m^2 for rotor termination, while for the parallel direction this was as high as 4.3 A/m^2 and for the oblique direction this was even higher at average of 5.8 A/m^2. Thus, comparing these three different directions of current density magnitudes, the shock vector directed in perpendicular direction could terminate the rotor with 16% lesser magnitude compared to parallel direction and with 38% reduction as compared to oblique direction. The initial results are encouraging that the defibrillation along the axis perpendicular to the rotor axis can terminates the rotor with a lower shock magnitude as compared with other directions.

IV. Conclusion

In this work we have studied the impact of directional shock vector in modulating (or) terminating the rotor using a monodomain cardiac model. The initial results are encouraging that directing the shock vector perpendicular to the rotor axis terminate them at lower magnitude of current densities compared to parallel and oblique directions with a minimum reduction of 16%. These results although obtained using simple monodomain cardiac model with isotropic diffusivity, demonstrates potential in further exploring the effectiveness of shock vector orientations. In continuation to these results, we are currently extending the simulations to a biophysically detailed bidomain cardiac model incorporating fiber information and with multiple rotors, which will validate our hypothesis in a realistic cardiac model.

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