FEM Evaluation of the Novel Cardiac Defibrillation Electrode Placement

Elham Khosrowshahli[1] **and Aleksandar Jeremic**[2]

[1]School of Biomedical Engineering, McMaster University, Canada
[2]Department of Electrical and Computer Engineering, McMaster University, Canada

Abstract— Defibrillation is used to treat patients with certain heart malfunctions. Different external defibrillation systems use two electrodes to deliver current to heart to regain normal beat. Successful defibrillation is determined by the amount of current delivered to myocardium, the amplitude of which depends on the impedance seen by defibrillator. Therefore, in order to gain higher current in the heart, this impedance should be minimized. All attempts to reduce this impedance is focused on decreasing external components like pad-skin impedance. But, in this paper the goal is the reduction of the internal component which is the impedance of the current path in torso by adding additional electrode according to parallel impedance rule of electric circuit theory. The new proposed defibrillation electrode placement is analyzed using developed electric circuit and Finite Element Method models.

1. INTRODUCTION

Defibrillation along with artificial breathing and certain medications is an important part of the process of treating patients with heart dysfunctions, such as ventricular fibrillation and ventricular tachycardia which may lead to death if the patient does not receive proper attention immediately. Investigation of current influence on heart beat started after the invention of glass capacitor in 1745, which is capable of storing electric charge and delivering it as a static shock. Several fibrillation and defibrillation experiments were conducted on animals and humans without the knowledge of the phenomenon at early time [1, 2]. The first documented report on the effect of electric current on ventricular fibrillation was published in 1849 by Carl Friedrich Wilhelm Ludwig and his student Moritz Hoffa [3]. Later, in 1899 Jean-Louis Prevost and Frederic Battelli noticed that although certain amount of electrical current can cause ventricular fibrillation, larger levels of current can reverse the damage and restore normal heart beat [4]. The first documented defibrillation on a human was conducted by Dr. Claude S. Beck in 1947. He applied the electric shock directly to the heart when the chest cavity was open during a surgery, and could regain young patient's heart beat [5]. The first reported closed chest defibrillation was performed by Paul Zoll in 1955 using defibrillator built by Electrodyne [6]. Since then several variations to the classic defibrillation method like automated external defibrillators (AED) [7], implantable cardiovascular defibrillators (ICD) [8] and wearable cardiac defibrillators [9] have been proposed. Also, the waveform of defibrillator voltage has been changed during this period. At first, alternative voltage was used for defibrillation. Later, in 1946 Gurvich and Yuniev introduced the use of DC voltage in defibrillation and reported that applying a single discharge of a capacitor is more effective than the application of alternative voltage [10]. Following this finding, Gurvich also introduced the biphasic waveform for defibrillation in 1967 for the first time [11]. Few years later, this waveform became the standard waveform of defibrillation in Soviet Union. But, it took some time to be verified and used in western countries as well. Now, biphasic is the preferred waveform for defibrillation.

Successful defibrillation depends on the voltage gradient or current density in myocardium [12, 13] which is determined by total current delivered to chest and current distribution in torso according to the impedance profile of it. The current is the function of defibrillator's voltage and the total impedance seen by defibrillator. The impedance consists of several components, one of which is the impedance between the pad or paddle and skin. This element may be reduced by the application of appropriate available gels and/or increasing the pad size. But, practical issues and reducing current density and hence, current delivered to torso prevent from increasing electrode size beyond the optimum value, which is 8–12 cm in diameter for human applications [14, 15]. Another component of this impedance is the impedance of current path between two points on the skin under pads on the chest. It is not easy to calculate this impedance because of the presence of several organs with complicated shapes and diverse electrical properties in torso which results in highly inhomogeneous medium and therefore complex current profile. Despite of this complexity, transthoracic impedance can be reduced using a simple rule of electrical circuit theory which says that the equivalent impedance of two parallel impedances would be smaller than each of them. This can be achieved by introducing the third electrode to defibrillation system. The role of this electrode is to create parallel current paths to the existing ones in torso and decrease the equivalent impedance seen by defibrillator which results in higher current delivered to the chest when the same defibrillator voltage is applied. Consequently, smaller voltage and energy is needed to deliver certain amount of current to the heart.

In this paper, the proposed method is analyzed by two approaches. A circuit model of defibrillation system is used to show how the extra pad decreases the applied voltage to deliver the same current to heart by creating parallel impedances. Also, a Finite Element Method (FEM) model is developed to investigate the method considering more details of the body. Effects of several configurations of the new pad placement on the current passing through heart is also analyzed using FEM model.

2. THEORY AND MODELING

There are four paddle/pad placements with no significant reported difference in results used in defibrillation which are anterior-apex, anteriorposterior, anterior-left infrascapular, anterior-right infrascapular [16]. The common feature of all methods, which are called conventional methods in this paper, is that all of them use two electrodes to apply defibrillator voltage to the patient's chest, that makes current to pass through the path created in torso between them, and consequently through the heart to achieve desired level of voltage gradient/current density in myocardium to reverse fibrillation. This phenomenon can be modeled with an electrical circuit consisting of a voltage source with the amplitude of defibrillator's voltage and the combination of number of impedances which resemble different components of the impedance seen by defibrillator. This model is shown in Fig. 1. In this model, V_c is defibrillator's voltage, Z_c resembles all impedances between defibrillator and skin, including impedances of cables, electrodes and pads, impedance between pad and skin and also part of the body impedance, Z_p is the impedance of parallel current path to the heart, Z_{s1} and Z_{s2} are body impedances in series with heart, and finally Z_{heart} is the impedance of heart. This model is a simplified explanation of defibrillation, since impedances of complicated current paths in torso are modeled as few single impedances, and used to describe the concepts of the new method. More precise models developed to confirm the results of this model, is presented in subsequent parts. Defibrillator's voltage needed to deliver desired current I_{heart} to the heart is calculated using (1).

$$V_c = I_{\text{heart}} Z_c \left(1 + (Z_{s1} + Z_{\text{heart}} + Z_{s2}) \left(\frac{1}{Z_p} + \frac{1}{Z_c}\right)\right) \tag{1}$$

(1) shows that desired heart current depends on defibrillator's voltage, and equivalent impedances of current paths in the body and the impedances of equipments outside the body. Therefore, in order to reduce required defibrillation voltage to achieve desired current in heart, impedances in the circuit should be decreased or the arrangement is changed to gain smaller equivalent impedance. Body impedances cannot be changed, but some techniques such as larger pad size and lotion application between pad and skin can be useful and have already been used to reduce pad and pad-skin impedances [14, 15]. Impedances of body is a considerable part of the impedance seen by defibrillator. The idea of the new method is to reduce this impedance which is employed in addition to already used strategies.

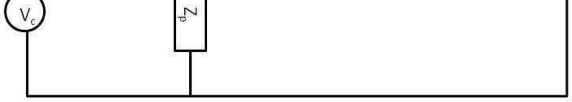


Figure 1: Circuit model of conventional defibrillation method.

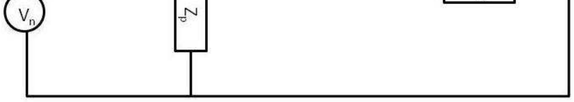


Figure 2: Circuit model of new defibrillation method.

Using parallel impedances rule in electrical circuit theory, the equivalent impedance of two parallel impedances is smaller than each of them, substantiates adding a parallel current path to the existing ones in conventional defibrillation methods to decrease the resulting impedance, and consequently voltage required to deliver the same current to the heart. Parallel current paths can be created by adding another electrode to the defibrillation system. The circuit model of the new technique is shown in Fig. 2. Here Z_{sp} is the impedance of new current path created by the third electrode. According this model, if I_{heart} is the desired current passing through heart, defibrillator voltage of the new method can be calculated using (2).

$$V_n = I_{\text{heart}} Z_c \left(1 + (Z_{s1} + Z_{\text{heart}} + Z_{s2} \parallel Z_{sp}) \left(\frac{1}{Z_p} + \frac{1}{Z_c}\right)\right) \tag{2}$$

Comparing (1) and (2), shows that since the equivalent impedance of $Z_{s2} \parallel Z_{sp}$ is smaller than Z_{s2} in conventional method, required defibrillator voltage is smaller in the new system. In addition, total power of defibrillator needed to deliver the same amount of current to the heart is smaller in this method, due to smaller voltage with the same current. Lower defibrillator voltage and power is mainly desired in portable and wearable cardiac defibrillators, where the battery size and life time are of great importance.

As it is stated before, circuit modeling of defibrillation is not precise enough to study exact effect of new electrode placement on current distribution in human body. Since differential equation which governs this phenomenon should be solved for an inhomogeneous medium containing several tissues with complex shapes and different electrical properties, numerical methods are practical for defibrillation studies. Finite Element Method (FEM) is one of these methods, that is used in this paper for further studies of the new technique. FEM solves following equation in conjunction with proper boundary conditions to obtain voltage profile in torso.

$$\nabla \cdot (\overline{\sigma} \nabla V) = 0 \tag{3}$$

where $\overline{\sigma}$ is electrical conductivity tensor and V is electric potential. Recall that the purpose of this study is to compare two methods of defibrillation and the exact FEM model of human's upper body which includes every single detail restricts simulation flexibility to study different electrode placements, a geometrically simplified FEM model is developed. In this model, although complicated anatomy is avoided, most of organs including lungs, heart, skletalmuscle, liver, small intestine, fat and skin are incorporated. The model of torso and different included organs are shown in Fig. 3. Dirichlet boundary condition is applied to areas which resemble pads and needed electrical properties are taken from [12, 13, 17].

Because this is not a model based on real images from MRI or CT like models in [12, 13, 18], actual threshold level of current density and voltage gradient for successful defibrillation cannot be assessed. But, simple geometry allows simulating several electrode placements of both conventional and proposed method, and investigating the effect of variant third electrode placement on defibrillation current.

To investigate the efficacy of the new technique, total current density in heart is calculated for two conventional electrode placements and is compared to the new method when the third

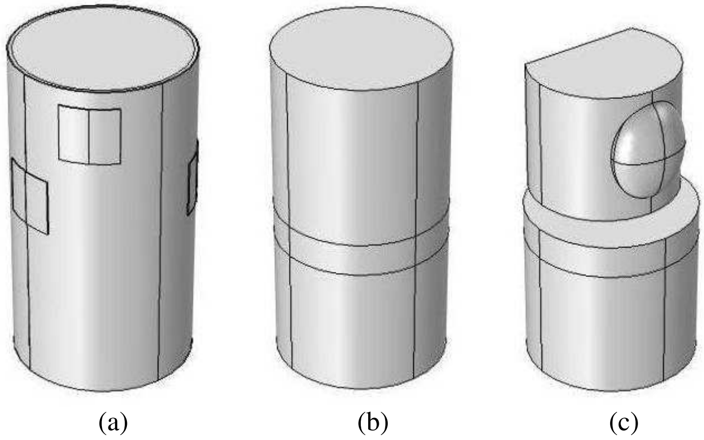

(a) (b) (c)

Figure 3: FEM model of torso for defibrillation (a) pads, skin, fat (b) skeletal muscle, liver, small intestine (c) lung, heart.

pad is added to the existing ones in different locations. For better interpretation of results, each pad position is determined by its height from the bottom of the model which is shown by z and measured in centimeters and the angle between body's sagittal plane and the pad counterclockwise. The angle is measured in degrees and shown by $theta$. z and $theta$ axes and their directions are shown in Fig. 4.

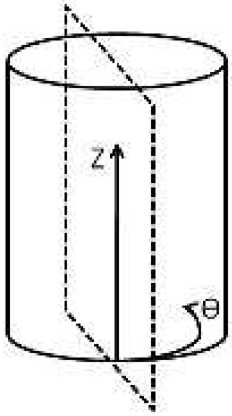


Figure 4: z and $theta$ axes.

3. RESULTS

FEM simulation is performed for two conventional pad placements, where pads are placed at $(z_1, theta_1, z_2, theta_2) = (40, 0, 30, 90)$ and $(z_1, theta_1, z_2, theta_2) = (45, 315, 30, 90)$ to obtain the total current density in heart due to the defibrillator's voltage. To study the performance of the new method, the third pad is added to each conventional layouts, and total current density in heart is calculated. The additional pad is placed on $z = 30$ and $z = 40$ at eight different $theta$s at 45 degrees steps, except where it overlaps the already placed pads of conventional system. Simulations are done with same defibrillator voltage for both conventional and new method. The arrow diagrams of current density for conventional pad placement at $(z_1, theta_1, z_2, theta_2) = (40, 0, 30, 90)$ and one of the simulated new method pad configuration where the third pad is located at $(z_3, theta_3) = (30, 135)$, are plotted in Fig. 5. In this figure arrows show the paths of the current in torso, and

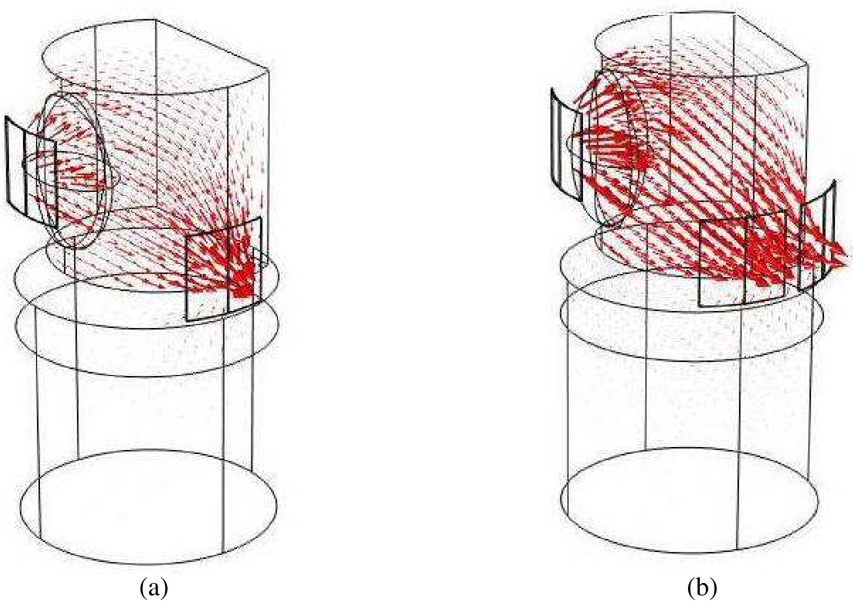
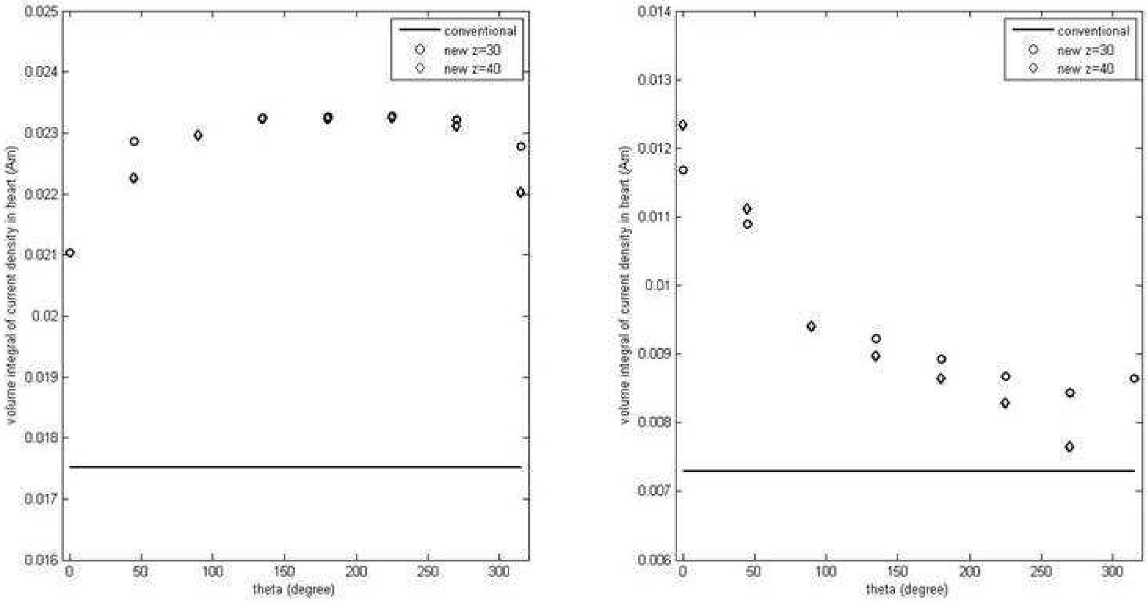

(a) (b)

Figure 5: Arrow diagram of current density in torso. (a) Conventional method, (b) novel method.



(a) (b)

Figure 6: Total current density in heart for different conventional and novel method configurations. (a) $(z_1, theta_1, z_2, theta_2) = (40, 0, 30, 90)$, (b) $(z_1, theta_1, z_2, theta_2) = (45, 315, 30, 90)$.

it is seen that in new method new current paths are created towards the third pad, parallel to the paths in Fig. 5(a). Total current density in heart for all simulated pad layouts summarized in Fig. 6 shows that including additional electrode increases current density in heart as predicted by circuit model due to creating new current paths parallel to the existing ones in torso, and results in the decrease of the impedance seen by defibrillator. As seen in Fig. 6, the position of the third pad affects the amount of heart current increase, such that in first conventional placement, the current is increased by almost 30% neglecting where the third pad is placed. While, when the second conventional layout is used, the location of the third pad affects dramatically the amount of current increase from almost zero in $theta = 270$ to 50% in $theta = 0$.

Therefore, it is verified that the new technique can be considered as a more efficient defibrillation method by reducing the needed voltage and power to send the proper amount of current to the heart comparing to conventional methods. Using this technique can lead to reduce the battery size of portable and wearable defibrillators and increase their life time. However, further studies must be done using more precise models derived from actual MRI or CT images which consider more anatomical details to determine the best positions of pads to get the desired heart current with the application of smaller voltage.

4. CONCLUSION

A novel electrode placement for external defibrillation is proposed. Based on electric circuit theory, the new method increases the current sent to the heart with the application of the same voltage by creating parallel impedances in torso, and consequently reducing the total impedance seen by defibrillator. A circuit model of defibrillation is used for preliminary study of proposed method. Also, for more comprehensive investigation, a FEM model of torso is developed, and several electrode layouts are analyzed. The results are in agree with the outcomes of the circuit model. Therefore, this method can reduce required voltage to deliver the same amount of current to the heart for successful defibrillation. It is desirable in situations when electric power supply is limited, like portable or wearable external defibrillators, where new method could help to increase battery life time or decrease the battery size.

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