

# ESTIMATION OF EFFECTIVE PAD POSITIONS DURING CARADIOVERSION USING 3-DIMENSIONAL FINITE ELEMENT MODEL

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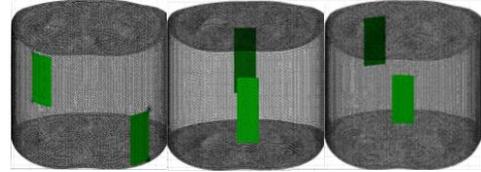
## INTRODUCTION

Cardioversion is a treatment for atrial fibrillation (AFib), atrial flutter (AF), and ventricular tachycardia (VT). For cardioversion to be successful, it is necessary that a significant mass (>95%) of the myocardium cells are depolarized [1]. The mass of cells undergoing depolarization is significantly influenced by the amount of current reaching the myocardium; this includes not only the magnitude of the current but also the spatial distribution of the current density in the heart [1]. A non-uniform current density distribution has a higher probability of re-inducing arrhythmia, thus leading to refrillation [2]. This distribution of current density is primarily dependent on the position of the pads.

The most common pad positions used during cardioversion are the Antero-Posterior (AP) and Antero-Lateral (AL) position. Some studies suggest the AP position to be more effective than conventional AL position. These studies have shown lower TTI and higher success at lower energy level for the AP position [1] [3] [12]. However, other works report both positions to be equally effective, claiming that the position of the electrodes does not affect the efficacy of cardioversion [4] [5] [7]. Lack of agreement regarding the effect of pad placement and the most suitable position have made the protocol for cardioversion clinician specific, with some preferring AL and some AP position during treatment.

In this research, we examine the effect of pad positions through simulation, using the finite element method (FEM). This permits a better understanding of the effects of pad position on cardioversion success with clinicians.

Back (Posterior view)



Front (Anterior view)

Figure 1: AL (Right), AP1 (Middle), and AP2(Right)

## METHODS

Three paddle positions (Figure 1), which are predominantly used for cardioversion are: Antero-lateral (AL), Antero-Posterior1 (AP1) and Antero-Posterior2 (AP2). The positions are compared in terms of:

i) amount of current density reaching the heart, ii) current density distribution uniformity, and iii) minimum voltage and defibrillation energy required to defibrillate the heart.

### A. Computational Approach of FEM

The potential distribution in a volume conductor is given by Maxwell's equations. Taking into consideration that the body is a source-free region and neglecting the effect of temporal variations due to the frequency and conductivity of the body tissues, Maxwell's equation is reduced to [7]:

$$\nabla (\sigma \nabla \phi) = 0 \quad (1)$$

where,  $\sigma$  is the conductivity of the medium, and  $\phi$  is the scalar potential. Equation (1) is a Laplace equation that defines the relationship between conductivity and potential distribution. Neumann boundary condition [7] is imposed on equation (1), which states that current flux density normal to the outer surface is zero

everywhere, except at the places where the electrodes are attached. That is:

$$\sigma \frac{\partial \phi}{\partial \hat{n}} = \begin{cases} J & \text{electrodes} \\ 0 & \text{elsewhere} \end{cases} \quad (2)$$

Imposing the above boundary condition, equation (1) is numerically solved for the potential distribution in the heart using FEM.

### B. Finite Element Model of the human thorax

A 2-Dimensional (2D) thoracic cross-sectional Computerized Tomographic (CT) scan from a normal person was obtained to identify the contours of the thoracic wall and the lungs. These contours were imported into MATLAB R2010a. A 3-dimensional finite element mesh was constructed using Netgen v.4.9.13 [8] from these contours, assuming that the body is symmetric along the chest region (Figure 2). The EIDORS algorithm [9] was employed to simulate the electrode geometry and current stimulation pattern.

This model assumes that all the regions are isotropic (i.e., conductivity of the tissues are same in all the direction). Conductivity is assigned to each volume element that corresponds to the region in the body that the element represents. The model takes into account five different tissues: cardiac muscle, lung, bone, fat, skin and skeletal muscle. Conductivity values used in this model is listed in Table I.

Table I: Tissue Conductivities

Tissue	Conductivity(S/m)
Lung	0.089
Heart	0.5
Ribs & Spine	0.01
Fat	0.05
Muscles	0.25

### C. Electrode Placements

Two rectangular shaped (11.1 cm X 6.9 cm) electrodes, similar to the Kendall Medi-Trace 1710H Defibrillation Electrodes were modeled on the surface of the thorax. These electrodes were placed at AA, AP1 and AP2 positions (Figure 1).

### D. Computation of Defibrillation Parameters

The potential and current density distribution throughout the heart were solved by simulating a current of 25 A through the pads. The input current considered is the average of the range of current required for a successful defibrillation for a biphasic defibrillator [6] [10].

The mean, maximum and minimum current density in the heart was determined for each pad positions. Studies have shown that defibrillation is successful only when an electric field of 5 V/cm is achieved for 95% of the heart and cardiac damage starts to occur at a potential gradient of approximately 50 V/cm [11]. Taking these numbers into consideration, we calculated the minimum current density required to defibrillate the heart ' $J_{th}$ ' and minimum current density that could result in cardiac dysfunction ' $J_d$ ' which in our case were 0.25 mA/mm<sup>2</sup> and 2.5 mA/mm<sup>2</sup> respectively.



Figure 2: 3-D Human Thorax Model: Anterior view (Left), Posterior Side (Right). Dark Blue represents Ribs and spine, Red-Heart and Blue- Lungs.

The defibrillation threshold energy (DFT) is calculated using the energy equation,  $E = \frac{1}{2} CV^2$  where  $C$  is the capacitance, measured as 100  $\mu$ F for the HeartStart MRx defibrillator, and  $V$  is the minimum potential difference across the electrodes that defibrillated 95% of the heart.

Uniformity of current density distribution across the myocardium is measured using the Heterogeneity Index (HI). HI is a normalized estimate of heterogeneity and has been used as a measure of uniformity in various defibrillation studies [1] [2].

$$HI = \frac{P_{5-95}}{P_{50}} \quad (3)$$

## RESULTS

Figure 3 shows the current density and voltage distribution in the body for all the three positions. Table II provides the mean, maximum, and minimum current density in the heart for each pad positions, along with their HI.

Table II. Current Density Comparisons

Pad Position	$J_{avg}$ (mA/mm <sup>2</sup> )	$J_{max}$ (mA/mm <sup>2</sup> )	$J_{min}$ (mA/mm <sup>2</sup> )	HI
AL	0.6373	1.595	0.3481	0.8
AP1	0.5480	1.374	0.3716	0.5
AP2	0.5757	1.386	0.4245	0.4

For all three pad positions, the minimum and maximum current density are respectively higher than  $J_{th}$  and lower than  $J_{max}$ , which implies that the entire heart was defibrillated without causing any damage to the cardiac tissue. The HI shows a higher non-uniformity for AL as compared to the AP positions. The minimum potential distribution required to defibrillate 95% of the heart and the total resistance for each of the locations is shown in Table III. More energy is required for the AL position as compared to the AP positions. AP2 also shows lowest resistance value.

Table III: Current, Voltage and Energy requirement to defibrillate 95% of the heart.

Pad Position	Current required (A)	Resistance ( $\Omega$ )	Voltage (V)	$E_{th}$ (J)
AL	14.5	65.96	956.51	45
AP1	13.2	59.43	784.5	30
AP2	12.8	58.24	745.52	27

## DISCUSSION

Results of this study suggest that all three pad positions that were investigated are defibrillating the entire myocardium when simulated with a 25 A current amplitude.

From Table II, it can be noted that AL position offers the largest range for current density ( $J_{max}-J_{min}$ ). This indicates that in AL position, some portion of the heart receives a very high current and some very low. This is more evident from Figure 2a, where we can see that the current pathways are more concentrated along the thorax wall and the ventricles than the rest of the myocardium. This could be because the electrodes are placed in such a way that the current can complete its path via the conductive tissues, heart, and the chest wall rather than having to traverse through other portion of the heart that is surrounded by less conductive lung region. For the two AP positions, the mean, maximum and minimum current densities are similar.

AP2 offer more uniform conduction as compared to AL and AP1 since it exhibits a lower HI. Earlier studies have correlated HI index to the defibrillation threshold energy and it has been found that a uniform current distribution corresponds to a lower defibrillation threshold energy level [1]. This holds true for our case as well; the AP2 position, which provides the highest uniformity in distribution, defibrillates 95% of the heart with energy 40% and 10% lower than AL and AP1, respectively (Table III). Our results in reduction in the energy requirement for AP are consistent with the results shown in [1] [3] [12].

It can also be observed that the current required to achieve a successful defibrillation is lesser for AP2. This suggests that while defibrillating larger patients where less current reaches the heart, AP2 could prove to be more effective than conventional AL position. Further analyzing our data in table III, AP2 offers the least resistance pathway. One plausible explanation for AP2 offering more uniformity and lesser  $E_{th}$  and resistance could be that in AP2 position, the electrodes are placed in a way that it matches with the orientation of the heart, thereby defibrillating more volume of the heart than the other two positions.

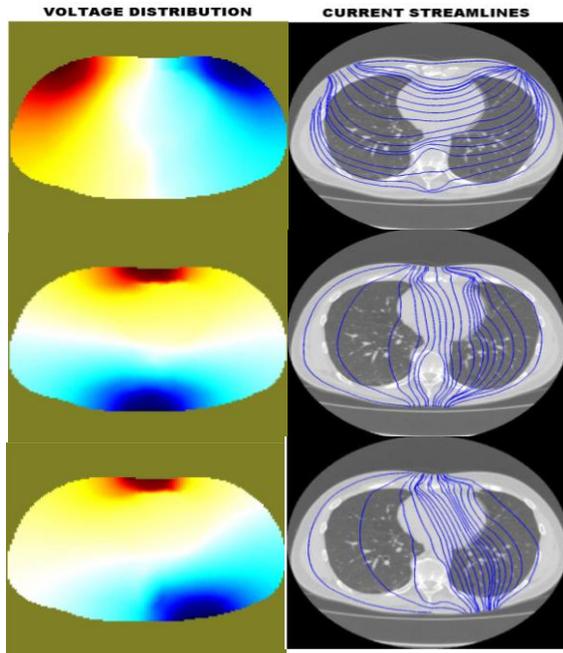


Figure 3. (Top)Voltage and Current Distribution for a. AL (Top), b. AP1 (middle), and c. AP2 (Bottom)

### CONCLUSION

Results in this study, suggest that the AL position is not as effective for cardioversion as AP. There is more current flowing towards the ventricular region for AL with 50% lesser conduction uniformity and 40% higher defibrillation energy than AP positions.

Comparing the two AP positions, the current density values are very close to one another; however, in terms of homogeneity, resistance and minimum energy required for defibrillation, AP2 is found to be more suitable during cardioversion.

Our FEM model has attempted to match a real patient condition during cardioversion, including electrode shape, size, positions, and defibrillation parameters (e.g., current and conductivity), which indeed is an improvement over the previous models [3] [7]. Results of these simulations are also in agreement to that measured experimentally using HeartStart MRx machine. However, it is limited by the accuracy of the tissue conductivities and anisotropic properties. The true anisotropic

representation of a human heart may result in altering the results. The models also does not account for factors such as patient's history of arrhythmia, anti-arrhythmia drug treatment, duration of arrhythmia, temporal variation of a biphasic waveform, which in a clinical scenario affects the cardioversion efficacy. Our future work includes refining the model so that it incorporates all these shortcomings and gives us a much better understanding of defibrillation.

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