Esophageal electric fields are predictive of atrial cardioversion success—a finite element analysis

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Background: Atrial fibrillation (AF) is a debilitating cardiac arrhythmia, one potential treatment of which is external cardioversion. Studies have shown external cardioversion success is affected by electrode placement and that esophageal electric fields (EEFs) during low strength shocks have the potential to be used in determining patient-specific optimal electrode placements during animal experiments. The objective of this study was to determine the relationship between EEFs and atrial defibrillation thresholds (ADFTs) during computer simulations using an anatomically realistic computer model of a human torso.
Methods: Over 600 electrode placements were simulated during which EEFs were compared to ADFTs.
Results: There was no single optimal electrode placement with multiple electrode placements resulting in similarly low ADFTs. There was over 40% difference in the ADFTs between the most and least optimal electrode configurations. There was no correlation between EEFs and ADFTs for all electrode placements, but a strong negative correlation when small shifts from clinically relevant electrode placements were performed.
Conclusions: These results suggest a small shifts protocol from clinically relevant electrode placements has the potential to increase the probability of successful cardioversion on the first shock and reduce the cumulative number of shocks and energy to which patients are exposed.

Keywords: Cardioversion; defibrillation; atrial fibrillation (AF); computer simulations

Introduction

Atrial fibrillation (AF) is the most common cardiac arrhythmia in the United States (1). It is characterized by disorganized cardiac electrical activity and an inability of the atria to effectively expel blood to the ventricles. One potential treatment of AF is external cardioversion, which includes the application of a strong electric shock through electrodes on the outside of the body. Studies have previously investigated the effect of electrode placement on cardioversion success, most attempting to find a universal, optimal configuration (2-7). The lack of agreement between these studies on a universal configuration suggests that patient-specific electrode placements may be the best way to optimize external cardioversion.

Two recent reports have described the results of preliminary studies investigating the role that esophageal electric fields (EEFs) could play in predicting patient-specific electrode placements (8,9). The first study reported a strong negative correlation between EEFs and atrial defibrillation thresholds (ADFTs) during preliminary computer simulations of 27 external electrode configurations (9). ADFTs are the minimum amount of energy required to successfully revert the heart to normal sinus rhythm. The second study reported negative correlations between EEFs during lower strength shocks

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Figure 1 Anterior view of the anatomically realistic, finite-element human torso model. The model consists of 14 anatomical regions including body surface, fat layer, skeletal muscle, lungs, heart, and the great vessels.

Table 1 Electrical conductivities of tissue regions in the model

Tissue region	Conductivity (mS/cm)
Aorta (13)	6.67
Body cavity (13)	2.22
Esophagus (13)	2.22
Fat (14)	0.50
Left atrium (13)	6.67
Left lung (15)	0.78
Left ventricle (13)	6.67
Myocardium (13)	2.50
Pulmonary trunk (13)	6.67
Right atrium (13)	6.67
Right lung (15)	0.78
Right ventricle (13)	6.67
Skeletal muscle (13)	2.50
Superior vena cava (13)	6.67

(1 Joule) and ADFTs recorded in six pigs (8). These studies both suggest that EEFs measured in the portion of the esophagus adjacent to the atria could be used to distinguish between various electrode placements and predict a patient-specific optimal configuration.

While the results of these preliminary studies suggest using EEFs to predict patient-specific electrode placements is plausible, both are based upon small numbers of measurements. The objective of the current study was to determine if the previously reported relationship between EEFs and ADFTs holds during a series of computer simulations consisting of over 600 external electrode placements.

Methods

Finite-element computer model

A three-dimensional, anatomically realistic finite-element computer model of a male human torso that has previously been shown to accurately predict clinically a relevant difference in ADFTs was used (*Figure 1*) (10). The geometry for the model was obtained from 90 transverse magnetic resonance images (MRIs) taken of the torso of a 190 cm tall, 80 kg healthy male (10-12). Tracings were made of the following 14 anatomical regions: body surface, skeletal muscle, fat layer, left lung, right lung, epicardium, left atrium, right atrium, left ventricle, right ventricle, superior vena cava, inferior vena cava, pulmonary trunk, and aorta. The coordinates from the tracings were triangulated and tessellated into 377,127 tetrahedral elements that were classified as one of the 14 anatomical regions.

Simulations

Torso geometry, cardioversion electrode placements, and tissue conductivities (*Table 1*) served as inputs for the model. The simulated cardioversion electrodes were a clinically realistic size of 100 cm^2. A total of 625 anterior-posterior (AP) electrode configurations were created by pairing a single electrode on the anterior chest with one on the posterior chest. *Figure 2* shows the total area of the torso body surface covered by the cardioversion electrode pairs.

For each electrode placement, a 100 V potential difference was simulated across the cardioversion electrodes. An average electric field value was calculated for the tetrahedral elements of the esophagus directly adjacent to the atria. An ADFT was then calculated for the electrode placement by scaling the applied potential difference to produce a minimum potential gradient (5 V/cm) throughout a critical mass (95%) of the atrial myocardium, as in (10). The EEF was squared because energy is related to the square of voltage. These steps were repeated for each of the 625 electrode placements. Both the
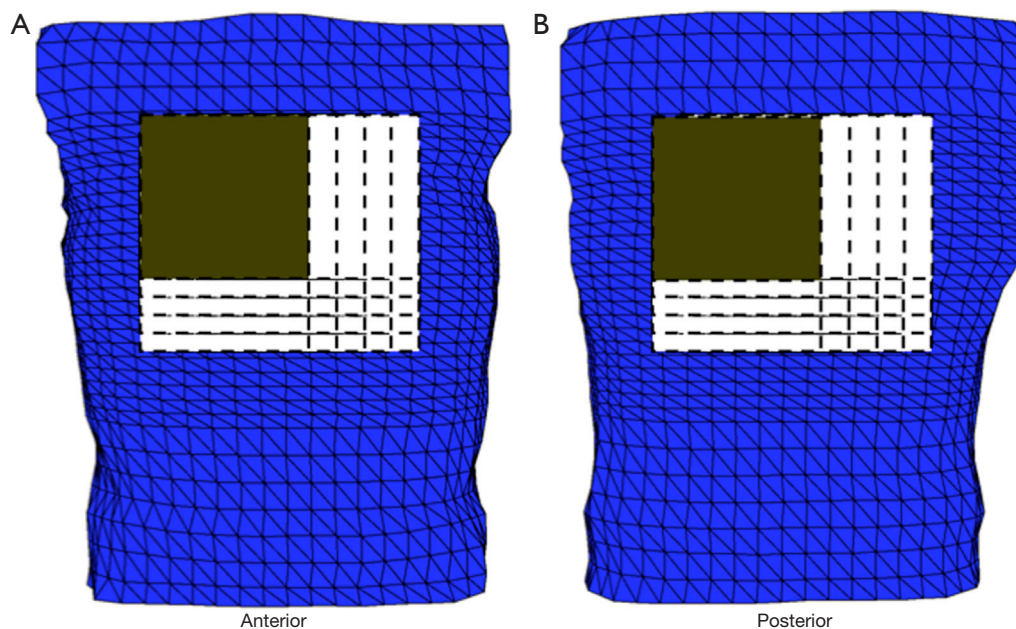
Figure 2 (A) Total area of the anterior and (B) posterior chests covered by all potential electrode placements. The black squares represent the size of one cardioversion electrode (100 cm^2). The dotted lines represent the edges of the electrodes at other potential electrode placements.
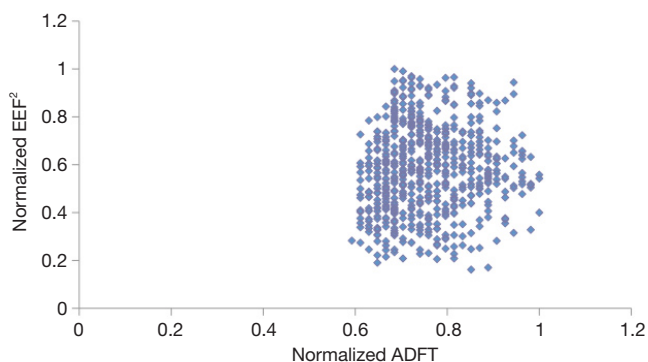

Figure 3 Normalized EEF^{2}s *vs.* normalized ADFTs for all electrode pairs. There was not a single optimal electrode placement for the 625 electrode placements. Instead there were multiple electrode placements that resulted in similarly low ADFTs. EEFs, esophageal electric fields; ADFTs, atrial defibrillation thresholds.

EEF^2 and ADFT were then normalized. Linear regression was performed to determine the correlation between the normalized EEF^{2}s and ADFTs.

Results

Figure 3 shows there was no relationship between normalized EEF^{2}s and normalized ADFTs when considering all 625 electrode placements. It also shows that of these 625 electrode configurations, there was not a single optimal electrode placement. Instead there were multiple configurations that resulted in equally low ADFTs.

Since there was no correlation between normalized EEF^{2}s and ADFTs for all placements, the authors next examined the correlation when small shifts, less than 2 cm, from clinically relevant electrode placements were performed. Electrode pairs were created by holding the central anterior electrode stationary and shifting the posterior in the same lateral row for a total of five electrode pairs (P$_L$), shifting the posterior electrode in the same axial column (P$_A$), or shifting the posterior electrode in a square pattern (P$_{SQ}$). Similarly, electrode pairs were created by holding the central posterior electrode stationary, while shifting the anterior electrode in the same lateral row as the posterior (A$_L$), shifting the anterior electrode in the same axial column as the posterior (A$_A$), or shifting the anterior electrode in a square pattern (A$_{SQ}$).

Linear regression was used to determine the coefficient of determination (R^2) and correlation coefficient (R) between normalized EEF^{2}s and ADFTs for each electrode-shifting pattern (*Table 2*). The percent difference between the maximum and minimum ADFT (ADFT$_{max-min}$) for each

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Table 2 Results from shifting one electrode while holding the other stationary

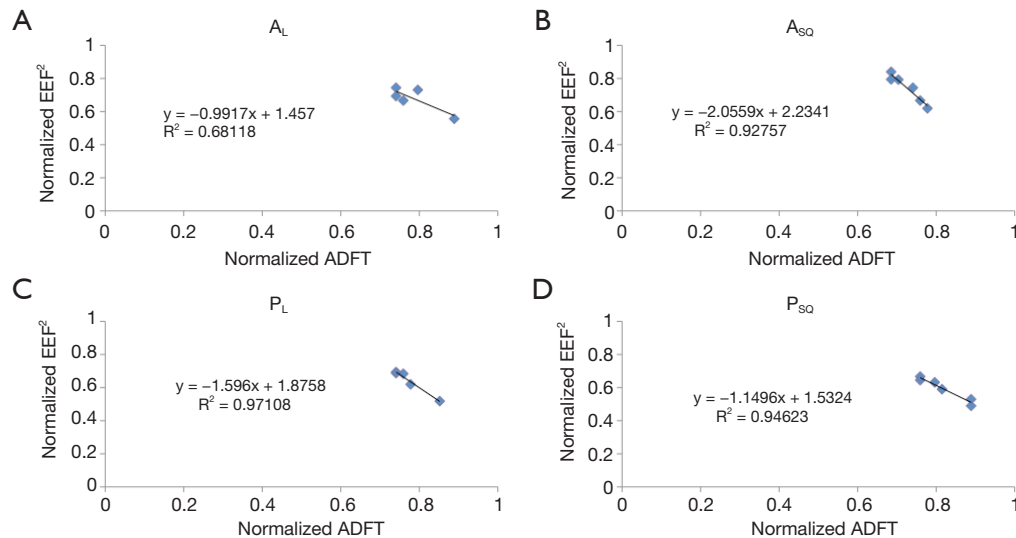| Variables	P_L	P_A	P_{SQ}	A_L	A_A	A_{SQ}
R^2	0.971	0.008	0.946	0.681	0.329	0.927
R	0.985	0.089	0.972	0.825	0.573	0.962
ADFT$_{max-min}$ (%)	11.2	1.80	13.0	14.9	13.0	9.30

ADFTs, atrial defibrillation thresholds.

Figure 4 The relationship between normalized EEF^{2}s and ADFTs when posterior electrode is held in the center and the anterior electrode is shifted (A) laterally and in a (B) square pattern. The relationship when the anterior electrode is held in the center and the posterior electrode is shifted (C) laterally and in a (D) square pattern. EEFs, esophageal electric fields; ADFTs, atrial defibrillation thresholds.

shifting pattern was also calculated. *Figure 4A-D* shows the relationships between normalized EEF^{2}s and ADFTs for P_L, P_{SQ}, A_L, and A_{SQ}.

Discussion

The relationship between normalized EEF^{2}s and ADFTs during external atrial cardioversion was investigated using an anatomically realistic, three-dimensional finite element computer model of the human torso. There was no correlation between normalized EEF^{2}s and ADFTs for the 625 electrode configurations overall. These results show there may not be a single, optimal electrode placement for each patient but instead several electrode placements that result in equally low ADFTs. There was over 40% difference between the smallest and largest ADFTs or the most and least optimal electrode configurations. This means there is potential to reduce required energy levels up to 80 J when considering the suggested initial energy of 200 J (16).

The authors next investigated if small shifts (<2 cm) from clinically relevant electrode placements could be used to reduce ADFTs. There was a strong negative relationship between normalized EEF^{2}s and ADFTs when the anterior electrode was held constant and the posterior electrode was shifted laterally in the same plane (R^2 =0.971) or in a square pattern (R^2 =0.946). There was a similarly strong negative relationship when the posterior electrode was held constant and the anterior electrode was shifted in a square pattern (R^2 =0.927) and a less significant relationship (R^2 =0.681) when the anterior electrode was shifted laterally in the same plane. There was no relationship when either electrode was shifted axially.

The described relationships may have potential application in the clinical setting. In practice, a clinician could position the external electrodes and apply a low-strength shock while measuring the EEF in the portion of the esophagus adjacent to the atria. The clinician could then reposition the electrodes, reapply the low-

strength shock, and again measure the EEF. This could be repeated for several electrode configurations with the full strength cardioversion shock being delivered through the configuration that resulted in the largest EEF. The idea being the electrode placement resulting in the largest EEF adjacent to the atria during the low strength would result in the largest electric field in the atria during the cardioversion shock increasing the chance of success during the first shock and reducing overall delivered energy when multiple shocks are required.

The findings that there is not a single optimal electrode configuration and that small lateral or square electrode shifts had the highest correlation with ADFTs could simplify implementation of the described application. It would be unrealistic for a physician to iterate through all possible 625 electrode configurations to find a single optimal placement. Instead it is far more reasonable to start with a clinically relevant electrode placement and make small shifts. The results of these simulations show small shifts in a square pattern around the central posterior or anterior electrodes can result in up to a 13% reduction in ADFTs and lateral shifts can result in reductions of up to 14 %.

Conclusions

In conclusion, a total of 625 electrodes configurations were simulated using a finite-element computer model of the human torso. There was no single optimal electrode configuration; instead multiple electrode placements resulted in similarly low ADFTs. Overall, there was no relationship between EEF^2s and ADFTs, but there was a strong negative relationship when one electrode was shifted while holding the other electrode constant. These results suggest it is plausible to use EEFs to optimize external atrial cardioversion electrode placements using a small shift protocol.

Acknowledgements

Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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