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Esophageal Electric Fields are Correlated to Atrial Defibrillation Thresholds: Towards Patient-Specific Optimization of External Atrial Defibrillation

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Abstract— **Studies have investigated the effect of defibrillator paddle position on the efficacy of external electrocardioversion of atrial fibrillation, without agreeing upon an optimal placement. We wish to investigate using esophageal electric fields (EEFs) to predict atrial defibrillation thresholds (ADFTs) on a patient-specific basis.**

We propose to (1) investigate the relationship between EEFs and ADFTs using computer simulations, (2) develop an esophageal probe that can accurately measure three-dimensional electric fields and (3) investigate the relationship between EEFs and ADFTs values *in-vivo*. Sixteen anterior-anterior and eleven anterior-posterior placements were simulated yielding a negative relationship between EEFs and ADFTs (R^2=0.91 and 0.93, respectively). An esophageal probe was developed that accurately measures EEFs. Animal studies showed a negative relationship between EEFs and ADFTs. This data suggests using EEFs to predict ADFTs on a patient-specific basis is plausible.

I. INTRODUCTION

ATRIAL fibrillation (AF) is a debilitating cardiac arrhythmia characterized by the failure of the atria to effectively expel blood to the ventricles. AF is the most common of all cardiac arrhythmias, affecting approximately 2.2 million people in the United States alone. Electrocardioversion is a common treatment of AF and approximately 25% of all attempts fail immediately [1]. Several recent publications have investigated the effect of defibrillator paddle placement on the amount of energy required to successfully defibrillate and the efficacy of electrocardioversion [2,3].

While studies have shown that defibrillator paddle placement can significantly affect energy requirements and efficacy of defibrillation [2,3], no consensus on an optimal placement has been reached. Previous clinical studies focus on finding one optimal electrode configuration, but evidence suggests patient specific placements may be the best way to increase defibrillation efficacy. One such study reported 9 of 10 patients were successfully defibrillated using an anterior-anterior (AA) electrode placement when an anterior-posterior (AP) placement had failed at maximum energy (360 J) [2]. Another study showed 8 of 12 patients were successfully defibrillated using an AP placement when an AA placement had failed at maximum energy [3]. This suggests that from patient to patient the optimal electrode placement may vary.

Increasing the efficacy of external cardioversion and lowering the amount of energy required has been shown to decrease both skin morbidity and post procedural pain [4, 5]. Koster et al. reported 66% of patients in their study complained of "more than trivial pain" when defibrillated using a monophasic defibrillator [4]. Pagan-Carlo et al. reported that patients who received high peak shocks (300 to 360 J) or cumulative shock energies as low as 350 J showed evidence of damage as indicated by leukocytes, eosinophils, and necrosis. Using a step up shock protocol, as is common in several recent studies [4, 6, 7], as many as 34% of patients are exposed to at least 350 J when being cardioverted [4]. Neal et al. reported a positive correlation between skin appearance and total energy delivered, between skin appearance and number of shocks, between comfort level and total energy delivered, and between comfort level and total number of shocks [6].

In this study, we define atrial defibrillation thresholds (ADFTs) as the minimum amount of applied energy required to terminate fibrillation in the atrial myocardium. In an effort to reduce cumulative shock energies and number of shocks delivered, we wish to determine if esophageal electric fields (EEFs) are predictive of ADFTs. We propose (1) to investigate the relationship between EEFs and ADFTs using computer simulations, (2) to develop an esophageal probe that can accurately measure three-dimensional electric fields and (3) to investigate the relationship between EEFs and ADFTs *in-vivo*.

II. METHODS

A. Computer Modeling

Computer simulations were performed using an anatomically realistic, finite element computer model. The

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computer model has been shown to predict clinically relevant differences in ADFTs [8].

Torso geometry, defibrillation electrode placements, and tissue conductivities served as inputs for the model. A 100 V shock was simulated between the defibrillation electrodes. The esophagus was separated into 1 cm sections in the axial direction. A weighted average electric field value was calculated for each of the four 1-cm sections of the esophagus nearest the atria. The computer model then calculated an ADFT value for each electrode placement. Linear regression was used to determine if a relationship exists between the weighted average EEFs and ADFTs.

B. Esophageal Probe Design

The esophageal probe consists of three commercial electrophysiology catheters including two Boston Scientific EP Technologies Polaris 9663S DX (Boston Scientific, Natick, MA) ablation catheters and one St. Jude Medical DAIG Livewire electrophysiology catheter (St. Jude Medical, Inc., St. Paul, MN). One platinum electrode was chosen from each of the Boston Scientific catheters and two platinum electrodes were chosen from the DAIG catheter to create three orthogonal electrode pairs.

The acrylic body is 1.5 cm in diameter and 6 cm in length (Figure 1). It consists of four columns, three of which are the electrophysiology catheters mentioned above and a fourth is a rigid, plastic column to provide support. The proximal top and distal cap were designed to maintain the distance between the electrodes. The distal cap is rounded at the bottom to ease the placement of the probe *in-vivo*.

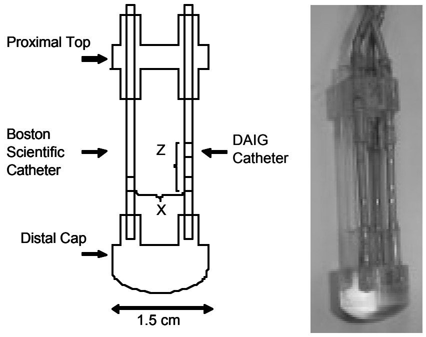

Fig. 1. Diagram and image of esophageal probe. Two electrodes were chosen on the DAIG catheter and one on each of the Boston Scientific catheters to create three orthogonal electrode

The esophageal probe was tested in a 27,000 cm^3 Plexiglass electrolytic tank. The tank has two 30 cm x 30 cm aluminum plate electrodes and was filled with a saline solution. The esophageal probe was positioned in the center of the tank. The plate electrodes were positioned in a parallel orientation and connected to a BOS/S power supply. Electric fields of 0.83, 1.67, 2.50, 3.33, and 4.17 V/cm were generated in the x, y, and z directions.

Regression lines were generated between electric field measurements and the applied electric field for each orientation. The slopes and intercepts of the regression lines were compared using a t-test.

C. Animal Studies

1) Animal Preparation: The study sample consisted of ten, 16.5-22.2 kg pigs of either sex. Each animal was anesthetized with an intramuscular injection of Telazol (1 mL/50 lbs). Anesthesia was maintained using sodium pentobarbital (65 mg/mL initially (8-10 mL), 2-3 mL as needed for maintenance).

Each animal was intubated and ventilated with room air. Core body temperature was maintained using a hot water blanket and a fluid warmer (Surgivet Hotline Fluid Warmer, Rockland, MA). Three standard electrocardiographic (ECG) leads were positioned on the animal, continuously monitoring cardiac rhythm throughout the experimental protocol. Temperature, oxygen saturation, and heart rate were recorded every fifteen minutes throughout the duration of the experiment.

The external jugular vein was surgically exposed and a bipolar pacing catheter (Medtronic Inc., Minneapolis, MN) was inserted. The pacing catheter was advanced into the right atrium and positioned so the distal tip impinged on the wall of the right atrium. Confirmation of appropriate positioning was acquired using fluoroscopy and intracardiac electrogram. The heart was then paced using a Medtronic A-V Pacing System Analyzer 5311B (Medtronic, Inc., Minneapolis, MN) to ensure adequate atrial capture. The esophageal probe was inserted into the esophagus using a laryngoscope and positioned near the atria using fluoroscopy.

2) Electrophysiological Study: Three AA and three AP electrode placements were used in this experiment. A Medtronic Physio-Control Series 70 DC defibrillator (Medtronic, Inc., Minneapolis, MN) was used in this study.

Prior to each induction of AF, the animal received succinyl choline (0.5 mg/kg) in order to reduce motion artifact due to skeletal muscle contraction during shocks. The pacing catheter was connected to a Tenma Audio Generator 72-505 (Tenma, Centerville, Ohio). A 1 V p-p, 50 Hz sine wave stimulus was applied for 10 seconds to induce AF.

All shock strengths were selected using a Bayesian up-down protocol [9]. Figure 2 shows the four-shock ADFT protocol. Upon the first successful induction of AF (>5seconds) for each electrode placement, a single 19 J shock was delivered to terminate AF. If the 19 J shock terminated AF, AF was induced again and a shock of 11 J was delivered. If the 19 J shock failed to terminate AF, a shock of 28 J was delivered. This up-down procedure was continued, with the energy level of the next shock dependent on the success or failure of the previous shock. The outcome of the fourth and final shock determined the ADFT for that electrode position. If any shock induced ventricular fibrillation (VF) a rescue shock of 200 J was delivered. If VF persisted, a second 200 J shock was delivered. At least ten minutes elapsed after successful termination of VF before the shock protocol was continued.

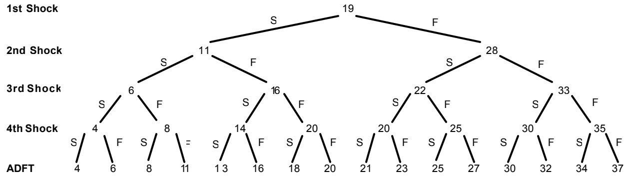

Fig. 2. The complete ADFT protocol. Each value represents the delivered energy (J) based upon success (S) or failure (F) of the previous shock.

The EEF during the initial 19 J shock for each electrode placement was compared to ADFTs. Linear regression was performed to determine the relationship between EEFs and ADFT values.

III. RESULTS

A. Computer Modeling

Sixteen different AA and eleven different AP electrode placements were created by shifting electrodes from clinical placements. Linear regression was performed to determine correlation between ADFTs and EEFs (Figure 3, $R^2 = 0.91$ and $R^2 = 0.93$, respectively).

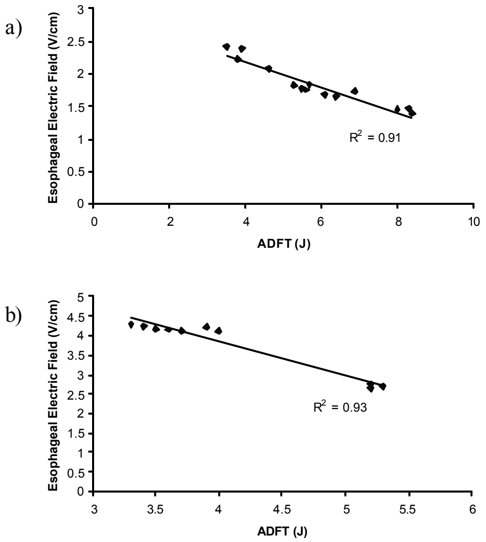

Fig. 3. Computer simulation EEFs versus ADFTs for both a) AA and b) AP electrode placements.

B. Esophageal Probe Design

Figure 4 shows applied electric field versus measured electric field for three parallel plate orientations. Regression lines were computed for each applied field orientation. The slopes and intercepts were compared to determine the coincidence of the regression lines. The slopes ($p<0.001$) and intercepts ($p<0.05$) of the regression lines are statistically the same. The slopes of the regression lines for the electric field applied in x, y, and z orientations were 1.02, 1.03, and 1.00, respectively.

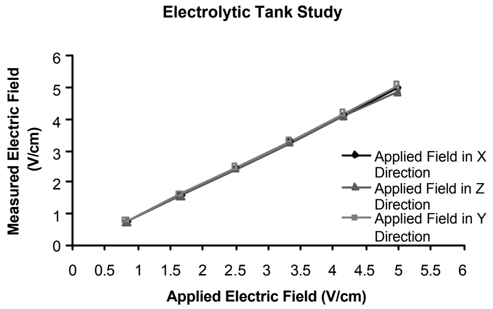

Fig. 4. Measured electric field for each applied electric field in the x, y, and z directions

C. Animal Studies

Five of ten animals completed the entire defibrillation protocol. Several animals were unable to complete the protocol due to equipment failure, inability to induce AF, or inability to defibrillate without inducing VF.

The EEFs during the initial 19 J shock for each electrode placement were compared to ADFTs (Figure 5). Again linear regression was performed to determine the relationship between EEFs and ADFT values for each animal.

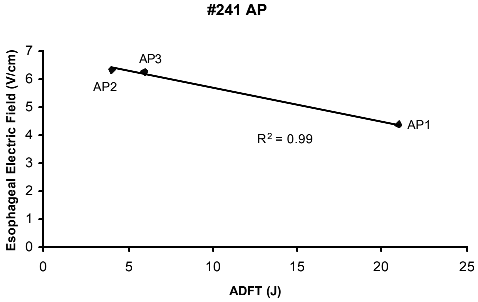

Fig. 5. Esophageal electric fields versus ADFTs for AP placements of animal #241.

IV. DISCUSSION

A. Computer Modeling

Simulations performed using the sixteen AA placements and eleven AP placements reported strong correlations between ADFTs and EEFs (R^2=0.91 and 0.93, respectively). The slopes of the regression lines were both negative, but differed significantly. This indicates that there is a relationship between EEFs and ADFTs, but that it may be different for AA placements and AP placements.

B. Esophageal Probe Design

The esophageal probe was used to make electric field measurements between three orthogonal parallel plate configurations in an electrolytic tank. The slopes and intercepts of regression lines fit to the data were compared and found to be statistically the same. The slopes of the x, y, and z directions were 1.02, 1.03, and 1.00 respectively, suggesting a 1:1 ratio between applied and measured electric fields and that the esophageal probe accurately measures three-dimensional electric fields.

C. Animal Studies

The EEF during the 19 J initial shock for each electrode placement was then compared to its corresponding ADFT. Since all electrode placements receive the 19 J shock, comparing it to ADFTs should provide similar information to that of applying a low strength measurements. The slopes were all negative, indicating a negative relationship between EEFs and ADFTs. R^2 values range from 0.085 to 0.994. Approximately 38% of R^2 values were above 0.9 and 50% were above 0.8. These values indicate a strong relationship between EEFs and ADFTs for almost half of the animals.

The negative relationship between EEFs and ADFTs in vivo was as expected. Again at a lower ADFT we would expect a higher EEF. The negative relationship also compared favorably with the negative relationships found during the computer simulations.

D. Limitations

The accuracy of the ADFT calculation is dependent upon the ability to accurately deliver energy. The defibrillator used for this study was an older model and required manual charging. We estimate the error in delivered energy to be approximately 10%.

The pig size varied between 16.4 and 22.2 kg. These size variations can lead to differences in body impedance, in turn affecting the amount of energy delivered to the heart. Also, variations in physical anatomy of the animals could account for some small R^2 values. Furthermore, the small number of electrode placements for each animal (i.e. small number of data points for linear regression) could result in large errors in the presence of outliers.

V. CONCLUSION

The ultimate goal of this work will be to develop a protocol to determine patient-specific electrode placements. The clinician would position the esophageal probe near the atria and then deliver a series of small strength shocks at several external electrode placements. The clinician would deliver the defibrillation strength shock at the electrode placement that resulted in the largest EEF.

Since all animals received a 19 J shock, comparing the EEF during the 19 J shock to its corresponding ADFT may provide similar results to that of small strength stimuli. The same was done in the computer model, by comparing the EEF during the 100 V shock to ADFT for each electrode placement. For the computer model and approximately 40% of the animals, there was a strong correlation between EEFs and ADFTs. This data suggests EEFs may be used to predict the location of patient-specific optimal electrode placements.

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