An Interactive Computer Model for Defibrillation Device Design

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Abstract

We have developed an interactive computer model for defibrillation device design utilzing the Utah Torso Model [1]. This system allows researchers to interactively design and place electrodes into a high-resolution finite element model of the human thorax to investigate fields generated from electrical shocks. Several quantitative measures are used to determine the efficacy of different electrode configurations thus providing a useful tool for evaluating a wide variety of electrode configurations in an efficient manner. Currently the most promising electrode configuration candidates are being tested in animals as well as in clinical enviroments.

Keywords: Defibrillation – Interactive Computer Model – Finite Element Method

Introduction

To stop the aberrant rhythms that characterize fibrillation, electrical shocks are delivered to the heart, the process of defibrillation. The design and placement of defibrillation electrodes is a critical issue for effectively restoring normal rhythm. Inefficient electrode design and placements can require larger quantities of current that can cause significant damage to the heart. In the past, researchers would use several series of animal trials to estimate effective electrode locations. Computer models have recently become sophisticated enough to assist in studying the defibrillation problem. Early computer models usually required significant amounts of time to construct and change model paramaters such that relatively few electrode configurations have been simulated [2]. We have developed a defibrillation modeling system that allows a researcher to interactively design and place electrodes into a high-resolution finite element model of the human thorax (the Utah Torso Model). The advantages of this system are that different electrode combinations can be tested computationally reserving the most promising candidates for animal studies. By reducing the number of experiments, there is the potential for tremendous savings in device design and development costs.

Model Construction and Electrode Design

The Utah Torso Model [1, 3] was derived from MRI scans and digitized to provide the boundary points defining the major electrically relevant anatomical regions including subcutaneous fat, skeletal muscle, lungs, ribs (clavicle and sternum), epicardium, epicardial fat pads, blood cavities (atria and ventricles), and the major blood vessels (pulmonary artery and vein, aorta, superior and inferior vena cava, subclavian, innominate and azygous veins). Figure 1 depicts a cutaway of the model highlighting the different anatomical regions.

Rectangular shapes were chosen for the subcutaneous patch electrodes and cylinders were chosen for the internal electrodes. The electrodes were deformed to fit inside the major vessels and/or to conform to the ribs with an interactive modeling tool. Once the electrodes were defined, a volumetric mesh was generated by first creating a surface mesh consisting of triangles used to place the electrodes within the thorax surface triangles. Following the surface construction, volume points were automatically created and tesselated into tetrahedral elements using a Delaunay mesh generation algorithm [2]. Dirichlet boundary conditions were then assigned to the electrode surfaces. The model was defined by over 20,000 surface points (including the electrodes). The resulting volume mesh (we created nearly 50 unique meshes to handle over 170 different electrode combinations) ranged from 1.2 million elements to 1.5 million elements. The finite element method was then used to solve for the potential and current density distributions.

Defibrillation Criteria

Five different defibrillation criteria were used to determine the efficacy of various electrode configurations. These included *electrode voltage threshold (EVT)*, *efficiency (Eff)*, *damage*, *uniformity (Unif)*, and *lead impedance* Z_L. The EVT was defined as the voltage difference across the electrodes necessary to yield a gradient of either 5 V/cm, (monophasic shocks) or 3.5 V/cm, (biphasic shocks) in 95% of the heart tissue. The **efficiency** of the delivered shock was based on the ratio of the energy reaching the heart to the total energy delivered. The **damage** level was determined to be the percentage of heart tissue above a particular gradient level. The gradient level used for monophasic shocks was 50 V/cm and 70 V/cm for biphasic shocks. The **uniformity** of the delivered shock was based on the ratio of the peak electric field in the heart volume to the average electric field

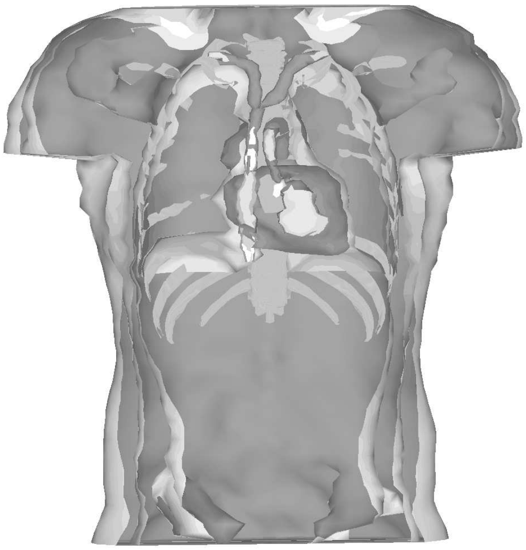

Figure 1 Cutaway of the Utah Torso Model showing the different anatomical regions included in the model.

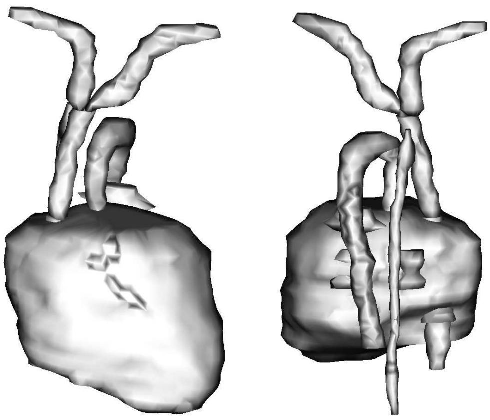

Figure 2 Figure showing the current density magnitude distributions for both the anterior and posterior views of the mediastinum for a typical defibrillation configuration.

	EVT			Damage			
	Mono	Bi	Eff	Mono	Bi	Unif	Z_L
1	801.8	561.3	18.7	14.3	3.0	14.0	48.5
2	389.7	272.8	17.2	3.5	0.02	7.8	34.6

Table 1 A sample comparison of the defibrillation criteria results for two different cases. Case 1 is for an anode and cathode lead system. Case 2 uses the same lead system as case 1, but it also includes an anodal subcutaneous patch electrode.

in the heart volume. It ranges from 1 for a perfectly uniform field to ∞ for a very non-uniform electric field. The **lead impedance** is the impedance across the electrodes and is commonly determined in actual experimental and clinical settings. This serves as an additional check of the model to experimental data.

Results

Over 170 different electrode combinations were implemented and computationally tested with this interactive modeling tool. Preliminary results showed that several of the defibrillation criteria parameters were within the ranges measured in clinical and experimental settings. Shown in Figure 2 is the current density distribution on the heart surface for a particular defibrillation electrode configuration. The darker regions indicate high current density magnitudes.

Table 1 compares two different electrode configurations that we explored. The first case refers to two cylindrical leads positioned in a vessel and blood cavity. The second case refers to the same lead system with an additional anodal subcutaneous patch. Case 2 with a subcutaneous patch has a significantly lower threshold voltage compared to case 1. Based on the criteria that smaller electrode voltage thresholds are better, case 2 could possibly merit further testing.

Conclusions

An interactive design tool has been developed to model defibrillation in humans. It has proven useful in efficiently evaluating a large number of different electrode configurations. Results of these simulation studies have suggested possible electrode combinations that are now being investigated in animal studies to confirm the model.

References

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Acknowledgments

This work was supported in part by a grant from Pacesetter, Inc. Special thanks to Ruth N. Klepfer for digitizing necessary additions to the geometry. Additional information regarding computational medicine research may be found on our WWW page, URL: http://www.cs.utah.edu/~sci.