Visualization of Defibrillation Simulation Using Multiple Transthoracic Electrodes

Joseph Qualls,1 David J. Russomanno,1 Amy de Jongh Curry,2 and Deepika Konakanchi2

1Department of Electrical and Computer Engineering
2Department of Biomedical Engineering
Herff College of Engineering
The University of Memphis
Memphis, Tennessee, 38152 USA

Abstract—DefibViz is a software tool for defibrillation simulation and the visualization of the resulting voltage gradient induced throughout the human heart and torso. This paper presents an extension to DefibViz that provides functionality for the interactive placement of multiple sets of transthoracic electrodes of varying shape, size, and applied voltage. Such a tool may provide biomedical engineers with additional insight into the efficacy of multi-electrode configurations as compared to the single pair of electrodes used in conventional defibrillators.

Keywords: Defibrillation simulation

1 Introduction

DefibViz has several research goals to help improve defibrillator design. These goals include facilitating the understanding of how electrode properties and placement affect the voltage gradient distribution throughout the torso and to determine optimal electrode placement to maximize defibrillation efficacy. Recently, there have been clinical studies that use multiple pairs of electrodes when applying a shock to a patient. Such an approach may be a promising alternative to the single pair of electrodes used in state-of-the-art defibrillators. Multiple pairs of electrodes may enhance defibrillator efficacy and may eliminate or improve upon other alternative techniques, such as internal cardioversion, which is an invasive surgical procedure [1].

When DefibViz was originally designed, it only supported the placement of a single pair of electrodes as is typical with the two-paddle, state-of-the-art defibrillators. DefibViz has been enhanced to support the specification, placement, simulation, and visualization of multiple-electrode configurations.

This paper briefly reviews DefibViz to provide context for the multi-electrode placement enhancement, which is the primary contribution of this paper. The reader is referred to Russomanno et al. [2] for a detailed description of the design and evaluation of DefibViz.

2 Background

2.1 DefibViz—Defibrillation Visualization

Patients that have dangerous arrhythmias or who are in cardiac arrest may be brought back to normal sinus rhythm through drugs or transthoracic defibrillation. Transthoracic defibrillation is the process of applying a voltage on the surface of the torso using external electrodes. DefibViz was originally developed to provide a simulation and visualization tool to study defibrillation thresholds and the distribution of the voltage gradient throughout the heart and torso induced from electric shock when applying two electrodes [2].

Other software packages have been developed that simulate defibrillation. Some of these packages include Defibsim [3] and others [4]. These tools do not provide an open-source development environment nor do they exploit a variety of visualization techniques to enable the user to fully explore the visual datasets. Some of these applications do provide source code but, due to their complexity, they are not easy to enhance with new features. DefibViz was designed to support modifiability, extensibility, and further experimentation with various simulation and visualization techniques, such as the placement of multiple electrodes, which is the focus of this paper.

Defibviz was developed as an open-source application to support subsequent improvement by the research community. The Visualization Toolkit (VTK) and TCL/TK were used in the implementation of DefibViz since they are both freely available and facilitate incremental development through an interpreted software environment [5-9].

DefibViz’s original graphical user interface (GUI) facilitated the interactive specification of a single pair of electrodes and their placement on the human body as shown in Fig 1. A finite element simulation was integrated within DefibViz to calculate the voltage gradient distribution throughout the torso and heart after a simulated shock. Once the voltage gradients have been computed, geometric and interactive volume visualization rendering techniques can be used to
explore the results of the defibrillation process. Fig. 2 illustrates the GUI that is used to select some of the available visualization techniques, such as the three-slice-plane method, the hinge-slice view [10], or geometric view. Fig 3 shows the geometric representation of the myocardium after defibrillation. These visualizations can be compared quantitatively and visually in any area of the torso or heart under a wide variety of conditions.

Fig. 1. Original DefibViz GUI for electrode placement.

Fig. 2. GUI for selecting visualization techniques.

Fig. 3. Geometric representation of the voltage gradient distribution in the myocardium after defibrillation.

3 Multi-Electrode Defibrillation

3.1 Clinical Research

Several factors determine the efficacy of transthoracic defibrillation, which is one of the most common methods to convert atrial fibrillation to sinus rhythm [2]. These factors include characteristics of the specific patient, such as transthoracic impedance, and the duration of atrial fibrillation prior to anti-arrhythmic therapy. Characteristics of the defibrillator electrodes, such as the position, size, and applied voltage of the electrodes, and the use of biphasic versus monophasic shocks also contribute to the efficacy of transthoracic defibrillation [11].

Multi-electrode defibrillation research encompasses several areas including the study of electrode properties and their effect on the defibrillation efficacy, improving techniques for higher patient survivability, and techniques to reduce damage to tissues resulting from the voltage applied to the body. Recently, clinical studies have been performed to study multi-electrode defibrillation on patients; therefore, the development of simulation software and visualization tools to complement multi-electrode clinical research is of interest.

One such clinical study involving multi-electrodes included fifteen patients with refractory atrial fibrillation [1]. Refractory atrial fibrillation is the condition in which the heart does not readily return to normal sinus rhythm with treatment. The patients of the study underwent defibrillation using two external defibrillators, that is, a four-electrode configuration.

These patients were subjected to a shock from two pairs of electrodes instead of the classical single pair of electrodes due to their unsatisfactory response to the shock from the single pair of electrodes. Traditionally, patients with refractory atrial fibrillation are often shocked with a conventional defibrillator multiple times in one procedure or several procedures over a series of
weeks. Currently, the alternative for these patients is internal cardioversion, which involves placing a catheter with electrodes near the heart through surgery.

In the clinical study, after using two pairs of electrodes for defibrillation, thirteen of the patients obtained sinus rhythm and eleven of the thirteen kept sinus rhythm for six months. Of the fifteen patients, none had any complications, such as significant hemodynamic compromise, congestive heart failure, higher atrioventricular block, stroke, or transient ischemic cerebral events [1]. From the results of this clinical study, using multiple transthoracic electrodes appears to be an attractive alternative to the invasive internal cardioversion procedure [11, 12].

3.2 Simulation and Visualization Tool
DefibViz has been enhanced to provide the researcher with the ability to simulate multiple electrodes and to specify the parameters of each electrode. The enhanced functionality includes fields to specify applied voltage, as well as the location and size of each electrode. The electrode placement GUI was enhanced to allow the researcher access to the multiple electrode simulation as shown in Fig. 4. To illustrate the flexibility of electrode placement in the new GUI for DefibViz, a random pattern of five electrodes was placed on the torso as illustrated in Fig. 4. A geometric rendering is shown in Fig. 5 of the resulting voltage gradient distribution throughout the torso after simulating the shock resulting from the five electrodes placed in the pattern illustrated in Fig. 4.

4 Experimental Results

4.1 Experiments
Experiments were performed that compared the defibrillation process using two electrodes versus four electrodes placed in similar positions on the torso using DefibViz. These experiments were created to emulate the clinical study previously described. There are several ways in which to compare the results of these two configurations of electrodes. One comparison can be based upon the atrial defibrillation thresholds (ADFTs). For the ADFTs, it is desirable to find an electrode combination and configuration which results in the least amount of applied energy (ADFT) to raise a critical mass of the atria 95% above a voltage gradient of 5 V/cm [13-15]. Lower applied energy implies less damage to surrounding tissues in the torso and other undesirable side effects. A second comparison involves examining the resulting visualization of voltage gradients produced by the electrode configurations to gain insight into the spatial distribution of voltage gradients.

For the experiments, the electrodes were placed on the anterior and posterior of the torso. For the anterior location, the electrodes were placed on the tricuspid auscultation area and for the posterior location; the electrodes were placed on the paravertebral area over the left scapula. For the two-electrode placement, one electrode was placed on the upper right anterior of the torso while the second electrode was placed on the
upper right posterior side of the torso as shown in Fig. 6. For the four-electrode configuration, the first two electrodes remained in the same position as in the first experiment while a third electrode was placed to the left of the anterior electrode and a fourth electrode was placed below the posterior electrode as shown in Fig. 7. The resulting geometric visualizations of the atrial myocardium from the two- and four-electrode configurations, respectively, are shown in Fig. 8. The resulting hinge-sliced visualizations of the entire myocardium from the two- and four-electrode configurations, respectively, are shown in Fig. 9.

**Voltage Gradient (V/cm)**

Fig. 6. Geometric visualization of the voltage gradient on the torso surface after defibrillation with one electrode placed on the anterior and one electrode placed on the posterior of the torso.

**Voltage Gradient (V/cm)**

Fig. 7. Geometric visualization of the voltage gradient on the torso surface after defibrillation with two electrodes placed on the anterior and two electrodes placed on the posterior of the torso.

**Magnitude of the Electric Field (V/cm)**

Fig. 8. Geometric visualization of the voltage gradient on the surface of the atrial myocardium after using two (top view) and four (bottom view) electrodes for defibrillation.
4.2 Discussion of Experiments

To reach the required voltage threshold of 5 V/cm, the two-electrode configuration required an ADFT of 61.2 J while the four-electrode configuration required an ADFT of 14.5 J. The ADFT of the four-electrode configuration required ¼ of the applied energy of the two-electrode configuration which may imply less damage to surrounding tissues in the torso. This would be a significant outcome. However, the results presented here are too preliminary to draw any significant clinical conclusions at this time. Nonetheless, the enhanced software tools provided by DefibViz were warranted as an additional investigative tool.

Inspection of Figs. 8 and 9 reveal distinct differences in the voltage gradient distribution throughout the atrial myocardium and full myocardium. In Figs. 8 and 9, the voltage distribution appears to reach a maximum on one end of the atrial myocardium and full myocardium for the two-electrode configuration. The four-electrode configuration appears to produce a more uniform distribution throughout the atrial myocardium and full myocardium. Further investigation is needed to determine whether these voltage gradient distributions throughout the myocardium have clinical significance, but as seen from the clinical research discussed in section 3.1, the four-electrode configuration produced better results than the two-electrode configuration for the patients in that particular study. Considering the lower ADFTs and the different visualizations of the voltage gradient distribution for the two versus the four electrode placements shown in this paper, multiple electrode configurations should undergo further study and the enhancements made to DefibViz should serve as a useful research software tool.

5 Conclusions

DefibViz is a software application that simulates and visualizes transthoracic defibrillation and was designed to be easily modifiable and extendable for continued development. Enhancing DefibViz to include multiple electrodes with varying properties provides an additional tool for biomedical engineers to investigate electrode placement, specifications, and the number of electrodes used for defibrillation. Multiple electrode research may lead to better defibrillation techniques that will decrease damage to body tissues and increase success rates for patients. DefibViz remains a work in progress in terms of both its simulation and visualization capabilities. DefibViz is freely available for research purposes through a request via the URL: http://engronline.ee.memphis.edu/nsf_ccli_0410290/defibViz.html.

Note: Many figures in this paper use a color legend which may not be consistent when printed in black and white. Please refer to the color version of this paper for the proper interpretation of the figure legends.

References


