BIVENTRICULAR DEFIBRILLATION WITH SEQUENTIAL SHOCKS USING PATIENT-DERIVED COMPUTATIONAL MODELS

D. Mocanu1, J. Kettenbach2, M. O. Sweeney3, R. Kikinis2, B. H. KenKnight4, S. R. Eisenberg1

1Department of Biomedical Engineering, Boston University, Boston, USA
2Surgical Planning Laboratory, Brigham and Women’s Hospital, Boston, USA
3Cardiac Pacing and Implantable Device Therapies, Brigham and Women’s Hospital, Boston, USA
4Heart Failure Research, Guidant Corporation, St. Paul, MN, USA

Abstract—Standard transvenous defibrillation is performed with implantable cardioverter defibrillators (ICD) using a dual-current pathway. The defibrillation energy is delivered from the right ventricle (RV) electrode to the superior vena cava (SVC) electrode and the ICD metallic housing. Clinical studies of biventricular defibrillation, which uses an additional electrode, placed on the left ventricular (LV) free wall, in conjunction with sequential shocks, have reported a 50% reduction in defibrillation threshold (DFT) energy. The goal of our study is to use computational methods to examine the biventricular defibrillation fields together with their corresponding DFTs, and to compare to standard defibrillation. Thoracic models derived from 5 patients were used in this study. The computational models were created from segmented CT images. The electric field distribution during defibrillation was computed using the finite volume method. The critical mass hypothesis was used to define a successful shock and to calculate the DFT. Our simulations show that the biventricular defibrillation lead system reduces the DFT by 30% in comparison to the standard configuration in 3 of the models and increases DFT up to 12% in the remaining 2. These results are consistent with clinical reports and suggest that patient-specific computational models may be able to identify those patients who could benefit from biventricular defibrillation.

Keywords – ICD, biventricular, defibrillation, sequential pulses, modeling, finite volume method.

I. INTRODUCTION

Ventricular fibrillation (VF) is a condition characterized by unsynchronized contractions of cardiac fibers that lead to ineffective pumping action of the heart and sudden cardiac death. Electrical defibrillation is the most efficient therapy to terminate VF by applying an electric shock to the heart. The implantable cardioverter defibrillators (ICD) is an electronic device designed to detect the onset of VF and to deliver an electric current to shock the heart back into its normal sinus rhythm. In the standard configuration, the ICD pulse generator is surgically implanted into the patient's chest wall, with two catheter electrodes inserted in the superior vena cava (SVC) and the right ventricle (RV). The shock energy is delivered via a dual-current pathway, from the RV electrode to the SVC electrode and the metallic housing of the pulse generator (RV→SVC+Can). Recent experimental studies of biventricular defibrillation [1], [2] have shown a reduction of up to 50% in defibrillation threshold (DFT) energy when using an additional shocking electrode, placed on the left ventricular (LV) free wall, in conjunction with sequential-shock waveforms. The goal of this study is to examine the biventricular defibrillation fields together with their corresponding DFTs and to compare to standard defibrillation.

II. METHODS

A. Image-Based Model Construction

All patients were imaged on a spiral CT scanning system post-implant, with the SVC and RV electrodes in place. Each of the patient-derived numerical models was constructed directly from the segmented CT images, using a structured meshing algorithm. Each voxel in the segmented image data set was defined as a volume element in the computational model. In all models, the LV electrode was created in the middle of the LV free wall, based on visual inspection.

B. Computational Approach

In the quasistatic approximation, the electric potential $\Phi$ is governed by

$$\nabla \cdot (\sigma \nabla \Phi) = 0$$

(1)

subject to boundary conditions: i) constant potential on the electrodes and pulse generator can (Dirichlet); ii) no current flux on the thorax surface (Neumann). Electrical conductivities were assigned to six tissue regions as follows: $\sigma_{\text{myocardium}}=2.5\text{mS/cm}$, $\sigma_{\text{muscle}}=2.5\text{ mS/cm}$, $\sigma_{\text{blood}}=8\text{ mS/cm}$, $\sigma_{\text{lung}}=0.7\text{ mS/cm}$, $\sigma_{\text{int}}=0.5\text{ mS/cm}$, $\sigma_{\text{bone}}=0.1\text{ mS/cm}$. Equation (1) was solved numerically by the finite volume method using I-DEAS software (Structural Dynamics Research Corporation, Milford, OH, USA).

C. Defibrillation Waveforms

The defibrillation waveforms considered were those used by Butter et al. [1]. In the standard configuration, the shock was delivered from RV to SVC+Can and had a biphasic waveform, with 60% tilt in the positive phase and a 50% tilt in the negative phase (Fig. 1a). For the biventricular defibrillation a 20% tilt monophasic shock was delivered from LV to SVC+Can, followed by a biphasic shock from RV to SVC+Can. The leading edge of the biphasic waveform was the same magnitude as the trailing edge of the monophasic waveform (Fig. 1b).

![Fig. 1. Shock waveforms: a) standard RV; b) biventricular](image-url)

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D. Solution Interpretation

For each simulation, the critical mass hypothesis was used to define successful defibrillation with minimum delivered energy: a successful shock must expose 95% of the ventricular myocardium to electric fields equal to or greater than the inexcitability threshold \( E_{\text{th}} \) [3]. In the case of standard defibrillation, the DFT was calculated using the biphasic inexcitability threshold \( E_{\text{th-bi}}=3.5 \text{ V/cm} \) [3]. In the biventricular defibrillation case, the electric fields produced by the monophasic and biphasic components of the sequential-shock waveform were computed separately. Elements in which the maximum monophasic field amplitude was \( \geq E_{\text{th-mono}}=5 \text{ V/cm} \) were assumed to be rendered inexcitable by the monophasic field. Elements in which the maximum biphasic field amplitude was \( \geq E_{\text{th-bi}} \) were assumed to be rendered inexcitable by the biphasic field. The 95% critical mass criterion was applied to the biventricular shock field to obtain the DFT. In computing the DFT from our simulations of biventricular defibrillation we assumed that the effect of the monophasic shock and biphasic shock were independent.

III. Results

The simulated DFTs obtained for five patient-derived computational models are shown in Table 1 for standard and sequential-shock biventricular defibrillation. Fig. 2 shows the spatial distribution of the monophasic and biphasic components of the combined field created to model the sequential-shock biventricular defibrillation.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Defibrillation Threshold Energy DFT (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard RV</td>
</tr>
<tr>
<td>AL</td>
<td>10.4</td>
</tr>
<tr>
<td>RO</td>
<td>6.3</td>
</tr>
<tr>
<td>EV</td>
<td>5.6</td>
</tr>
<tr>
<td>MA</td>
<td>5.0</td>
</tr>
<tr>
<td>FE</td>
<td>3.7</td>
</tr>
</tbody>
</table>

The weak field regions (\( E < E_{\text{th}} \)) associated with standard RV and biventricular defibrillation of patient AL are shown in Fig. 3.

!![Fig. 3. Weak field regions, patient AL: (left) standard RV lead system (the ICD catheter is shown in green); (right) biventricular lead system (LV electrode shown in white).]

IV. Discussion

It is well known that the standard ICD configuration creates a non-uniform defibrillation field, leading to weak field regions in the posterolateral LV. Biventricular defibrillation can potentially compensate for these weak fields by using an additional shocking electrode within or near these regions. Our patient-derived simulations show a 30% reduction in DFT for three of the five patients examined. In these patients, the addition of the LV electrode resulted in a more uniform field (and consequently, a lower DFT) in comparison to the standard configuration. The failure of the biventricular defibrillation to reduce the DFT in the remaining two patients indicates that LV electrode position and patient geometry play important roles in establishing a more uniform defibrillation field.

V. Conclusion

Our simulation results are consistent with experimental reports [1], [2] and suggest that patient-specific computational models may be able to identify those patients who could benefit from biventricular defibrillation.

REFERENCES