Transactions on Biomedicine and Health vol 1, © 1993 WIT Press, www.witpress.com, ISSN 1743-3525

A three-dimensional boundary element model of the electric field from implantable defibrillators

T.J. Gale, D. Kilpatrick, P.R. Johnston
& P.M. Nickolls
Department of Medicine, University of Tasmania, Hobart, Australia

ABSTRACT

The delivery of high energy shocks from implantable defibrillators is largely influenced by the design and configuration of the delivery electrodes. To optimise electrode design and placement, a 3-D boundary element model of the electric field from implantable defibrillators was developed. The model used approximately 3500 constant quadrilateral elements, constructed from MRI scans, and consisted of eight isotropic regions that represented the chest, heart, left and right blood chambers and vessels, lungs, spine and sternum. Additional regions represented epicardial, endocardial and subcutaneous electrodes. The governing Laplace equation was solved to find potentials and gradients throughout the thorax. This paper discusses the implementation of the model and presents results that show differences in the electric field between an endocardial and epicardial electrode configuration.

INTRODUCTION

The design and configuration of the delivery electrodes for implantable defibrillators directly affects defibrillation efficiency. Improvements in electrode design will result in many benefits including better defibrillator performance, increased probability of defibrillation, decreased risk of damage to cardiac tissue and extended defibrillator life.

The electrodes should impose an electric field throughout the ventricles that exceeds the defibrillation threshold–which is in the order of 500 V/m (Glass et al., [1]). However, the field is invariably non-uniform and will be greater than the threshold over most of the ventricles. For example, at least 15 times the required field (thus 225 times the required energy) is typically required with epicardial electrodes (Glass et al., [1]). It therefore appears that scope exists to significantly reduce the required field if a more uniform field can be achieved.

A three dimensional Boundary Element model was developed to compare the field produced by different electrodes. The model allows epicardial, endocardial and subcutaneous electrodes to be modelled in a realistic thorax and can be used to calculate potentials and gradients throughout the thorax and particularly in the heart muscle. One application of the model is to evaluate possible electrode configurations before animal or human experiments are done.

METHOD

In the model the thorax is treated as an outer region, representing the chest, within which are subregions, representing the internal organs and structures. The whole is considered a continuum and the regions isotropic. Electrodes are modelled either as additional regions, or as a boundary condition on the outer region. All the sources are thus incorporated into the boundary conditions and each region is source-free. Consequently, the electric field within each region is governed by Laplace's equation,

$$\nabla^2 u = 0. \tag{1}$$

Finding the electric field is then simply a matter of solving equation (1) by an appropriate numerical method, such as the boundary element method. The boundary element method was chosen here, due to the advantages in the discretisation of the regions over other methods such as finite element or finite difference. Applying the boundary element method (Brebbia and Dominguez, [2]) to equation (1), a set of simultaneous equations is constructed of the form

$$HU = GQ, \tag{2}$$

where H and G are $n \times n$ matrices dependent on the model geometry and the discretization of the surface elements, and U and Q are vectors of length n representing potentials and fluxes (respectively) on the elements in the model (n is the number of elements).

Applying the boundary conditions sets either the potential, flux or equilibrium conditions for each element and allows the combination and rearrangement of equation (2) over all the regions to form equation (3). In equation (3) matrix A and vector B contain known values while the vector X contains the unknown potentials and fluxes which can be found using a suitable solution method (Gaussian elimination was used here).

$$AX = B. \tag{3}$$

Once the potentials and fluxes on the boundaries of the regions are known, potentials and gradients at internal points are easily found using similar methods (Brebbia and Dominguez, [2]).

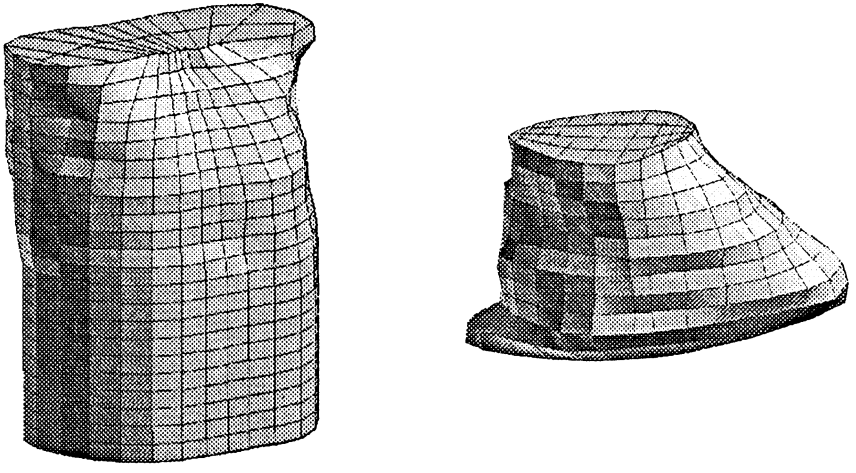


Figure 1: Boundary element mesh for the chest and heart

The model was tested on two types of thorax. The first was with regions that were shaped as cubes to enable verification against a finite element model. The second was with realistically shaped regions using approximately 3500 constant quadrilateral elements. In this case, each region of the thorax was constructed as a three dimensional surface, with the geometry coming from MRI scans of a 58 year old female. Figure (1) shows examples of the mesh that was used for the chest and heart.

A horizontal slice through the thorax, near the base of the sternum, further illustrates the geometry (figure (2)). Excluding electrodes, there are eight regions in the model, representing the thoracic tissue (comprising the chest wall, the mediastinum and tissue not in other regions), spine, sternum (not shown in the figure), left and right lungs, heart, right-side blood cavities (comprising the right ventricle, right atrium, inferior and superior vena cava, and the pulmonary artery) and the left-side blood cavities (comprising the left ventricle, left atrium and aorta). The conductivities of these regions, were 0.23, 0.00, 0.05, 0.18 and 0.67 $(\Omega m)^{-1}$, respectively.

The model accommodates three types of electrodes–epicardial, endocardial and subcutaneous. Epicardial and endocardial electrodes are modelled as additional subregions on the epicardium and in the right-side blood cavities, respectively, and subcutaneous electrodes are modelled as a boundary condition on the chest surface. Up to two epicardial, four endocardial (two touching the endocardium and two entirely surrounded by blood), and any number of subcutaneous electrodes can be used. The epicardial electrodes are configured to have a constant potential on their inner face with an insulated back, while the endocardial and subcutaneous electrodes have a

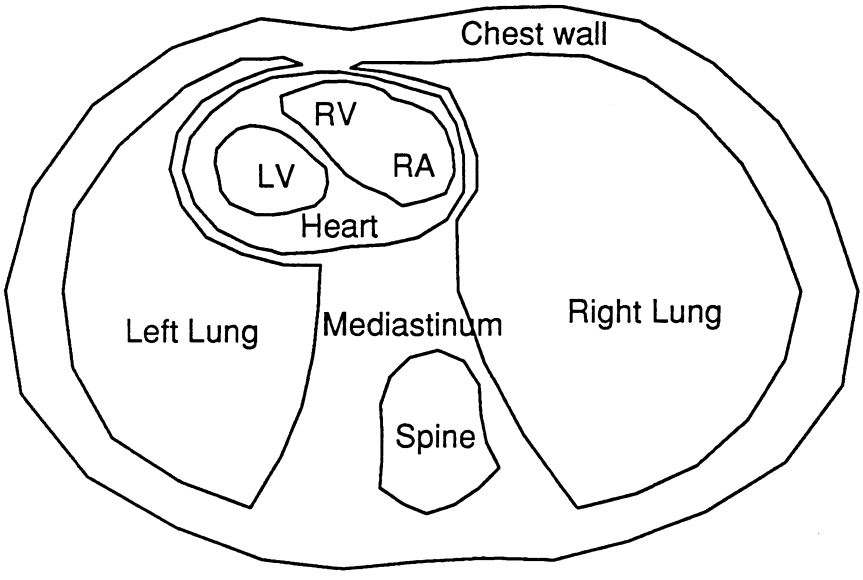


Figure 2: Horizontal slice taken through the model of the thorax near the base of the sternum. RV = right ventricle, RA = right atrium, LV = left ventricle.

constant potential over their entire surface. It is unnecessary to insulate the back of the subcutaneous electrodes in this model, because of their location on the outside of the thorax.

The requirement for electrodes to be modelled in different positions meant that it was desirable to have a reliable method for constructing the electrodes. The epicardial electrodes and the endocardial electrodes that touched the endocardium, were generated automatically using a purpose-written computer program after their location on the epi- and endocardiums was defined. Endocardial electrodes were generated around a centerline obtained as a cubic spline through a series of points in space, thus allowing the electrodes to be shaped to fit inside the blood cavities.

It can be seen that one of the benefits of using the boundary element method in this application is that the electrode configurations can be easily changed without the need for extensive remeshing. For example, the position of the endocardial electrode could easily be changed. Remeshing would be limited to ensuring the mesh was sufficiently refined in areas of high gradients, and, importantly, complex three-dimensional meshing would be avoided.

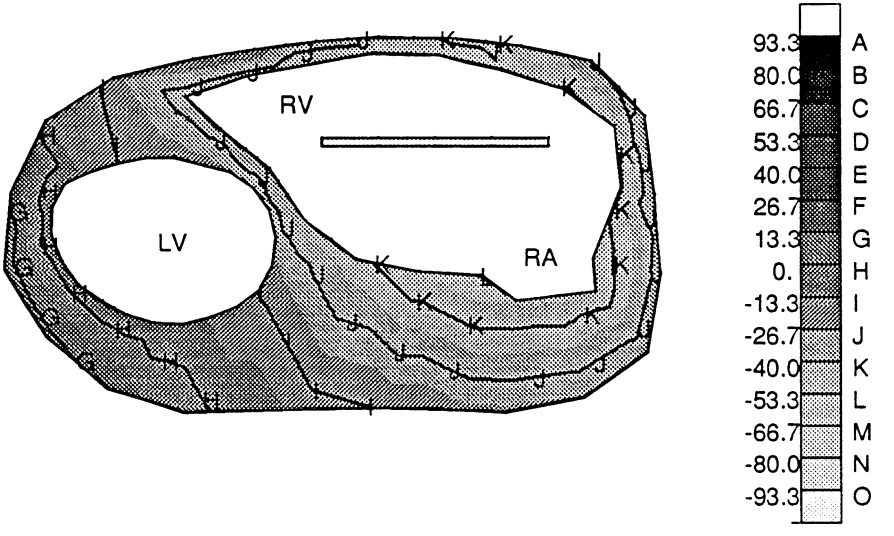


Figure 3: Endocardial and subcutaneous electrode pair. The subcutaneous electrode was on the left chest wall on the same horizontal plane as the endocardial electrode. The scale shows voltages on the contours.

RESULTS & DISCUSSION

Two electrode configurations have been evaluated. The first has an endocardial electrode (40 mm long and 3 mm in diameter) in the right ventricle and a subcutaneous electrode (covering an area of 50 cm^2) on the left chest wall on the same horizontal plane as the endocardial electrode. The second has two epicardial electrodes positioned either side of the heart and covering a total of 30 cm^2 (16 %) of the heart surface. In both cases a potential of ± 100 volts was applied across the electrodes.

Although results were obtained throughout the three-dimensional thorax, for simplicity they are presented here on two-dimensional slices taken through the heart. The slices lie on a horizontal plane passing through the left and right ventricles and the electrodes, and the results are contour plots of potential.

The results for the endocardial electrode configuration (figure (3)) show that having the endocardial electrode near the middle of the right ventricle induces voltage dissipation in the blood leaving only a relatively weak gradient through the heart muscle. Despite being weak, however, the gradient is distributed reasonably uniformly throughout the muscle and has a minimum value of approximately 800 V/m.

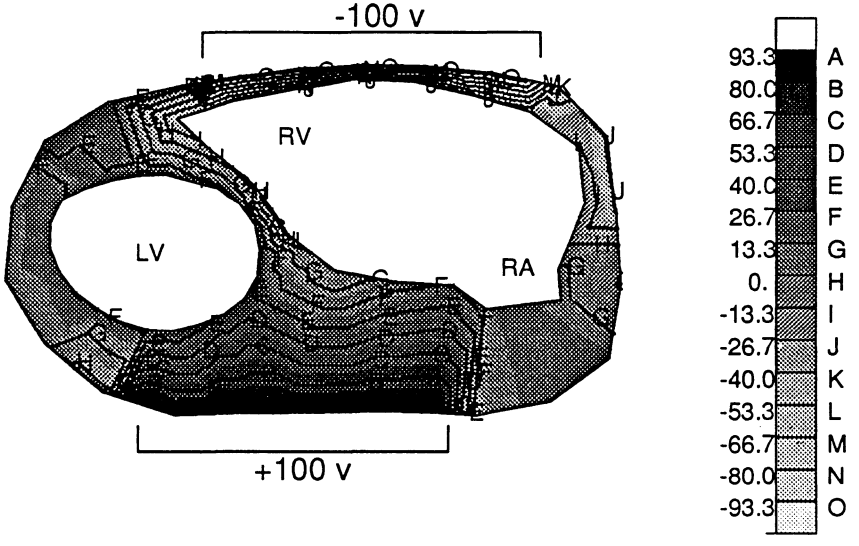


Figure 4: Epicardial electrode pair. The scale shows voltages on the contours.

Results for the epicardial electrode configuration (figure 4) show a markedly different potential distribution as the positioning of the electrodes forces the entire applied potential to be delivered across the heart. Consequently, there are high gradients in the heart muscle, especially underneath the electrodes. In this case, though, there is a large variation in gradient throughout the muscle, with a relatively low gradient on the left and right sides of the slice. It is particularly important to achieve a gradient above the threshold in the LV wall and although the observed minimum gradient in this region (approximately 530 V/m) is sufficient, it is interesting that the endocardial configuration has produced a better result. Probably a better position for the posterior epicardial electrode would be one that partially covers the left ventricular wall.

CONCLUSION

The boundary element model discussed here is effective in modelling the electric field from implantable defibrillators. The model allows different electrode configurations to be used with little penalty in terms of time taken for remeshing. Results have been presented that show significant differences between two types of electrode configurations.

REFERENCES

[1] Glass, L., Hunter, P., and McCulloch, A., editors. *Theory of Heart.* Springer-Verlag, New York, 1991.

[2] Brebbia, C. A. and Dominguez, J. *Boundary Elements An Introductory Course.* Computational Mechanics Publications, Southampton, second edition, 1992.