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Image Based Modeling of Defibrillation in Children

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Abstract - **Volume imaging, defibrillation electrode models, and finite element modeling are employed in patient-specific procedural modeling in pediatric patients with cardiac arrhythmias. Due to variable size and anatomy, these patients may not be well-served by devices designed for adult defibrillation. A pipeline for rapid creation of image based models that can be interactively interrogated to determine optimal defibrillation scenarios and preliminary proof-of-concept work are presented. This approach has potential clinical applications for therapy planning and broad applications for finite element modeling in anatomical models. Clinical studies investigating the effects of body size, habitus, and anatomical variation on myocardial voltage gradients are planned.**

I. Introduction

The development of digital volume imaging and image processing algorithms in medicine has created opportunities for therapy planning based on patient specific anatomy. This will be of great value to pediatric patients and those with congenital malformations, where assumptions of size and anatomical "normality" are invalid. In this project, we use volume imaging, defibrillation electrode models, and finite element modeling (FEM) to demonstrate the use of patient-specific procedural modeling in pediatric patients with cardiac arrhythmias. Preliminary proof-of-concept work has been achieved in creating a pipeline by which image based FEMs can be rapidly created and interactively interrogated to determine optimal defibrillation scenarios for these patients.

Standard strategies have been developed in adults that permit cardiac defibrillation to work with high reliability. External and internal defibrillation is less frequently needed in children, but among patients with congenital heart disease and hereditary forms of potentially lethal arrhythmia, the use of defibrillation devices (ICDs and AEDs) is widespread and the indications for use are becoming broad – more than

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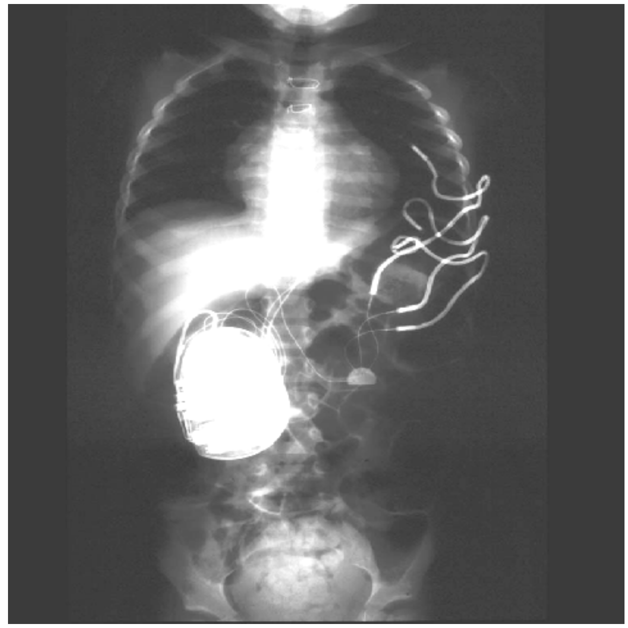

Figure 1. Clinically effective *ad hoc* strategy used for placement of subcutaneous electrode array and abdominal ICD placement in 2 y/o child with ventricular arrhythmia.

50 new ICD implants/yr occur at Children's Hospital Boston (CHB) alone. Because of limitations of body size and cardiac anatomy, standard adult ICD electrode placement is often impossible in children. A variety of *ad hoc* approaches to ICD implantation have been employed in these special populations, including placement of the ICD on the abdominal wall, use of subcutaneous thoracic and intrapericardial electrodes and placement of electrodes in the inferior vena cava [1,2,3]. These electrode configurations have not been optimized with respect to maximization of defibrillation efficiency or to minimization of potential myocardial damage due to locally high voltage and current gradients. To date there are no platforms for studies of defibrillation in children which have the ability to answer these questions, or even to generate appropriate testable hypotheses. The literature is similarly sparse on optimum paddle placement for external defibrillation in children, a topic of increasing significance given the emergence of public access defibrillation.

We present an approach to clinically relevant, patient-specific modeling of pediatric cardiac defibrillation. Our objective is to develop an open-source software pipeline which will allow the clinician to move rapidly from standard DICOM images of the torso and geometric descriptions of electrodes to treatment planning, using finite element modeling of a variety of clinically feasible approaches to

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defibrillation in children. Clinical question to be addressed using this approach will be: what are the effects of body size, habitus, and anatomical and surgical variation on the distribution of voltage fields in pediatric myocardium during defibrillation events? Our working hypothesis for this study is that clinically significant variations in myocardial voltage gradient will be predicted by our modeling approach, providing guidelines for future research in this area and ultimately refining clinical practice.

II. IMAGE-BASED CARDIAC BIOELECTRIC MODELING

We have used existing, modular open-source software to optimize segmentation of anatomical data, to create FEMs of the pediatric torso, and to model imposed or endogenously generated electrical fields of interest in the myocardium. Other investigators have published reports demonstrating the utility of finite element modeling (FEM) in adult torso models of standard defibrillation techniques [4-8]. These have been of value in understanding the induced electric field in the thorax using standard electrode and can placements in the right ventricle, superior vena cava and infraclavicular region. Defibrillation thresholds in FEMs of adults typically fall within one standard deviation of the mean defibrillation thresholds reported in clinical studies [9], and such models are also predictive of defibrillation efficacy and efficiency of various intravascular electrode configurations [9-11]. They can also be used to minimize high potential gradients which may contribute to cardiac damage and potential arrythmogenesis [12]. While these results are promising, clinical use of FEM has been limited by the time and expertise needed to create realistic torso and electrode models and manipulate them to provide useful data. This has prevented the clinical user from modeling of the optimal defibrillation power and electrode placement in a specific patient prior to actual implantation.

There are three unique aspects to the current approach. First, this is the first study using image based modeling to predict the function of standard, adult-designed electrical systems in the range of body sizes and types encountered in pediatric practice, and exploring the novel geometries which often must be used to implant devices in small patients and those with major abnormalities of cardiac anatomy (Figure 2). Second, although proprietary applications packages exist that are designed to facilitate anatomical segmentation and

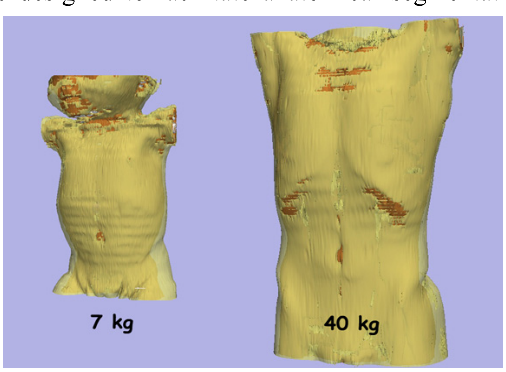

Figure 2. Age related differences in size and body habitus

conversion to finite element modeling these applications are relatively focused on specific medical applications (especially orthopedic FEM analysis) and opaque with respect to their proprietary meshing algorithms. We sought to create an open-source pipeline within 3-D Slicer and SCIRun for conversion of medical images to finite element models with broad application within the modeling community.

Third, we sought to insert appropriately shaped electrodes into user defined positions within imaging based models which to allow real time interrogation and visualization of voltage gradients in the myocardium and associated tissues as the positions of the electrodes are varied. Suitable modules are being created within SCIRun/BioPSE to allow this within any volume model.

III. PRELIMINARY RESULTS

To date, ~20 CT scans done at Children's Hospital since 2001 have been identified in patients with normal thoracic and abdominal anatomy, ranging from 7 mos – 16 yrs and from 7 – 63 kg. Several of these have been segmented using 3D Slicer, with identification of fat, muscle, bone, blood, myocardium, lung, liver/spleen, kidneys, bowel gas and abdominal viscera (Figure 3, prior page) [13]. The organ masks are exported from 3D Slicer as nrrd format datasets,

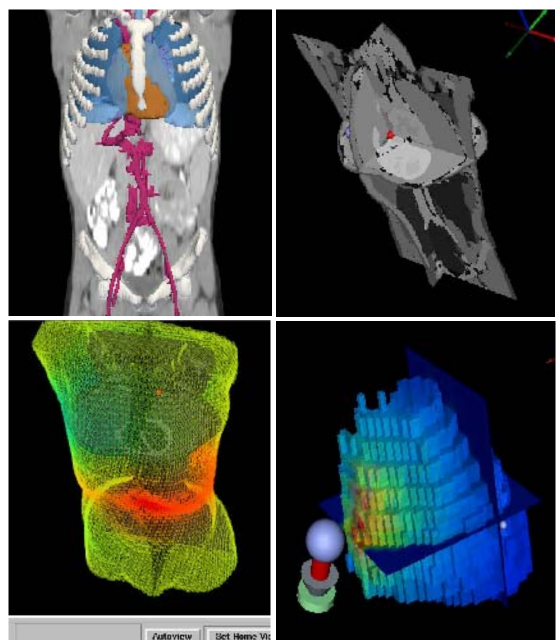

Figure 3. Upper left: Segmented torsos from a 40kg CHB dataset demonstrate anatomical detail in myocardial, vascular, lung and bone segments. Upper right: 3D rendering of same model with movable cutting planes for visualization. Lower left: Voxel based FEM mesh of model, demonstrating segmented data sections and color-mapped surface voltage in response to arbitrarily positioned thoracic dipole source. Lower right: Isolated myocardial compartment of same model showing local voltage distribution in response to adjacent dipole source.

and converted using the UNU toolkit to a composite volume with hierarchical determination of organ assignment made automatically for each voxel. Composite datasets are then imported into BioPSE/SCIRun, and conductivities for these organ domains (extracted from the experimental literature) are assigned to allow modeling of voltage fields and current flows [14,15]. The model is resampled and a mesh is generated using the FEM module with BioPSE/SCIRun; improved meshing algorithms are currently being implemented and may allow for more efficient variable density meshing of data sets (Figure 4).

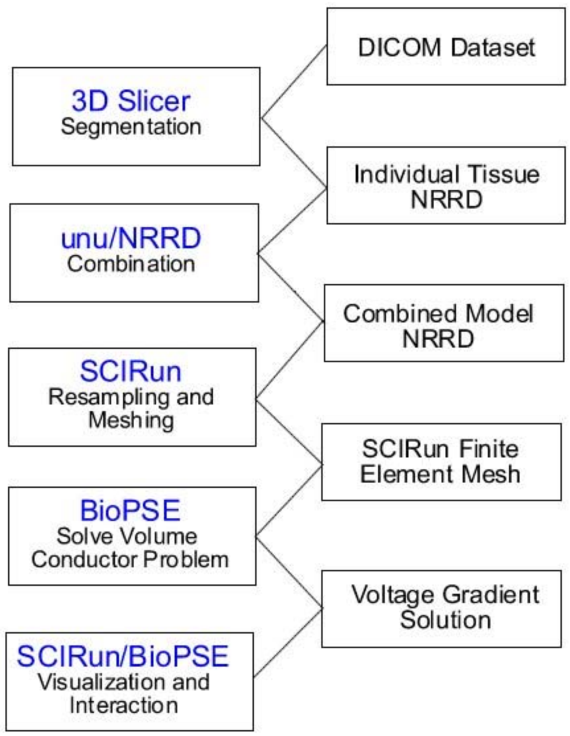

Figure 4. Flow chart of data and the individual tools utilized to create and visual image based finite element models.

After segmentation and creation of meshed and parameterized models, voltage values are inserted at specific model nodes to emulate the applied electrode voltages during defibrillation, and the volume conductor problem is solved with subsequent visualization of the resulting voltage gradients within the model (Figure 3, prior page). BioPSE/SCIRun modules for automatic modification of the meshed anatomical models to allow repeated interactive relocation of electrodes are in the final testing stages at SCI. The effect of the induced field on the myocardial volume can then be actively interrogated both visually and quantitatively. Preliminary development of this algorithmic pipeline has shown the feasibility of this seamless sequence of volume segmentation, mesh creation, and electrical modeling.

IV. FURTHER INVESTIGATIONAL PLAN

A. Development of pipeline for data analysis

Algorithms for automatic segmentation of torso anatomy – A variety of algorithmic approaches to segmentation have been deployed and developed in 3D Slicer, including template-based deformable nonrigid registration, level set and statistical techniques. The first approach for automated anatomical delineation is to warp segmented anatomy from several subjects into the subject data set to determine the most likely patient-specific segmentation [16]. This yields robust results on large organs, but is less effective for structures with considerable intersubject spatial variability (e.g. the vascular tree). For segmentation of patient specific models of vasculature, we have used level set methods (available in the 3D Slicer). A third possible approach to automated segmentation has been developed by Pohl at CSAIL MIT in collaboration with the SPL [17]. This method (also available in the 3D Slicer) combines the strengths of obtained with warping an anatomical atlas, with a statistical classifier to refine the precise localization of object boundaries. Existing segmentation algorithms will be modified to optimize their use in the thorax and abdomen for this application.

User defined defibrillation electrode geometries – Widgets are in development to enable structured modification of meshes to represent geometry of defibrillation electrodes. These support local alterations of the polygonal mesh and model boundary conditions to incorporate the electrodes into the complete simulation model. This will allow accurate modeling of the interactions of the electrodes with surrounding tissue.

B. Predictive modeling of pediatric defibrillation

Two retrospectively identified CT volume-imaging datasets have been gathered and will be used as the basis for further study. The first set consists of contrast-enhanced CT scans of the abdomen and thorax performed on children with normal anatomy and of body size from 7 – 63 kg, segmented into tissue domains of varying conductivities [18]. The second set consists of thoracic MRI studies in patients who have subsequently undergone ICD implantation and determination of defibrillation threshold testing. After modeling of the defibrillation voltage field in these models, histogram and color-map analysis of voltage gradient over myocardial nodes will be determined, to allow comparison of defibrillation efficacy and uniformity of the voltage field across the myocardium.

Modeling of external defibrillation – The hypothesis will be tested that patient size and the surface area and anatomical placement of external defibrillation pads affect the distribution of myocardial voltage gradients. For a given torso size, patients will serve as their own control, with multiple possible geometries tested in each torso model.

Modeling of implantable defibrillators – The hypothesis will be tested that variations in anatomical placement of internal defibrillation electrodes affects distribution of myocardial voltage gradients. Standard and nonstandard ICD implant geometries will be evaluated (abdomen to internal coil, abdomen to posterior epicardial coil, abdomen to posterior subcutaneous coil, thorax to IVC coil). Implant geometries will be identified which maximize the efficiency with which a homogeneous defibrillating voltage gradient is delivered to the myocardium, while minimizing adverse occurrence of high voltage gradients with potential for myocardial injury.

Validation of defibrillation thresholds (DFTs) – It has previously been shown that, in adult patients undergoing standard implants, DFTs were well predicted by FEM [19]. The hypothesis will be tested that similar validation methodology can be used to predict clinical DFTs in pediatric patients who have undergone thoracic MRI, ICD implant and subsequent DFTs.

C. Assessment of model parameter sensitivities – Features of the proposed modeling framework may prove to be computationally intensive, algorithmically unstable and/or dependent on prior conductivity data. The sensitivity of the model to variations in FEM density, anatomical detail and tissue conductivities will be systematically explored.

V. Conclusions

No technology or experimental data currently exists to guide defibrillation practice in the young patient. The patient-specific, model driven approach to therapy planning described here has the potential to affect design and application of defibrillation in these patients in a significant, immediate manner. Expedited defibrillation modeling may be expected to guide recommendations for external defibrillation practice and to become a practical tool to guide individual placement of ICDs. It will also benefit the adult population, serving as a tool for implementation of novel implant strategies and totally "leadless" ICD systems [20,21]. Clinical implementation will require considerable additional work outside the scope of this specific proof-of-concept proposal, including validation studies in animal and then clinical models, as well as product development effort.

Beyond defibrillation, this project will provide a model for the development of a variety of patient-specific, predictive physiological modeling for surgical and interventional procedures. Our group will move from the current study on to the development of this approach for noninvasive body-surface arrhythmia mapping for use as an adjunct to catheter-based intervention, employing the inverse solution in rapidly developed, electrically plausible models of the chest and heart (exemplary preliminary work from other investigators in this area includes Fischer and Rudy [22,23]).

Rapid development of computational models from volume image data is a subject of intense interest across a variety of application problems. We expect the production of an end-to-end system with clear potential for clinical impact will be of great interest to the medical modeling research community.

VI. Citations

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