# The Role of Volume Conductivities in Simulation of Implantable Defibrillators

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## Abstract

In the quest for patient specific models for predicting defibrillation efficacy, one of the questions is which tissue types to include into a volume conductor model of the torso. We present a comparison between a model consisting of 11 different tissue types to models with only a subset of of tissue types across a database of electrode orientations including transvenous, epicardial, and subcutaneous electrodes. The simulations show that the volume conductor models should at least include segmentations for the heart, lungs, blood, and bones, and possibly the fat layers and the amount of gaseous space in the stomach and intestines. The latter ones may be necessary for modeling subcutaneous electrode configurations and ICD "cans" in the abdomen.

## 1. Introduction

In order to provide better guidelines for the implantation of Implantable Cardiac Defibrillators (ICD) in pediatric patients, we are developing a new software tool that allows physicians to predict defibrillation efficacy prior to the actual implantation. One of the reasons for developing this tool is the difficulty that for pediatric patients there is no consensus for the best locations for the ICD lead placement [1]. Not only is optimal lead placement unknown, placement is often restricted due to the smaller patient size, abnormal anatomy, and other restrictions. Furthermore, there is a growing adult population in which standard approaches cannot be utilized as well as interest in a totally subcutaneous ICD which would simplify implant process and make ICD implantation more accessible.

One way to provide more insight into the dependence of defibrillation efficacy on the locations of the electrode leads, is by means of simulating the electrical field that is generated by means of an electrode configuration. By assessing the relative differences in electrical field strength inside the heart one can estimate which configuration will be more beneficial in terms of the region of the myocardium it targets, the maximum electrical field strength inside the myocardium and the homogeneity of the field.

In a previous study, we demonstrated that these electrical fields can be simulated and that they potentially could reflect the efficacy observed in patients[1]. This study was based on a series of models that made use of manually segmented CT-images. The latter images were used to describe the electrical properties of the torso. Although manually segmented CT-images are a good starting point for a prototype application, a more practical source for patient specific models would be the use of MR-images.

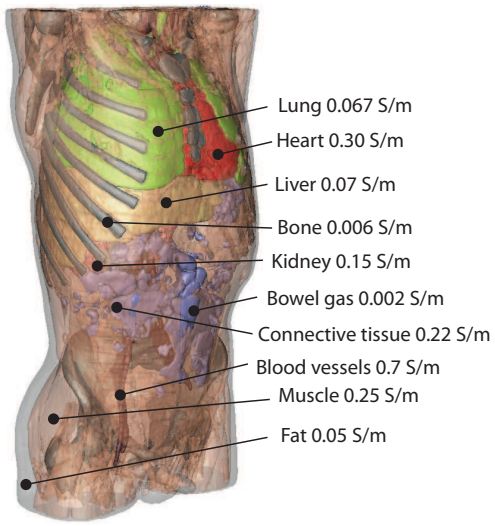


Figure 1. Volume conductor model of 10 year old patient. The different colors in the image represent the different tissue types. For each tissue in the model its specific conductivity is listed.

Whether one uses a model based on CT-images or MR-images, the manual segmentation of many tissue types re-

mains a labor intensive procedure and may void the benefits of computer simulation. In our current modeling pipeline the segmentation of torso models is the most time consuming part of the project, and hence developing algorithms to speed up this a process to a point where most or all of the segmentation is done automatically is one of the next goals. However before starting to optimize this process one of the crucial questions that remains is which tissue types are actually needed for the estimation of defibrillation efficacy. If one can eliminate the need for several tissue types in the model, it would ease the segmentation needs.

In order to investigate the need for certain tissue types in the segmentation, we computed the estimated defibrillation efficacy for many electrode lead configurations, while changing the number of tissues that were included into the segmentation. We used our previous model[1] that included 11 tissue types as a reference model and evaluated the change in predicted defibrillation energy needed for defibrillation while changing the setup of the model in terms of tissue types that were included.

## 2. Methods

### 2.1. Torso model

In this study we made use of three torso models which consisted of manually segmented CT scans of a 2 year old girl, a 10 year old boy and a 29 year adult male. The two pediatric cases were chosen to represent two different age groups, and the adult torso was included to compare results against other adult models for defibrillation.

The segmentation of torso was accomplished using the slicer software (www.slicer.org), and the segmentation process took about 40 hours per scan for a skilled physician. The tissue types that were included are: kidneys, liver, lung, bowel gas, muscle, fat, bone, heart (ventricles), heart (atria), blood, and connective tissue. An example of a model created from such a segmentation is illustrated in Figure 1. The figure also lists the conductivity assumed for each tissue type. This choice of conductivities was based on previous models from literature [1, 2].

### 2.2. Electrode Configurations

In order to simulate a clinical defibrillation scenario, the model needs to be augmented by electrode leads. In order to generate realistic scenarios a software tool was created within the SCIRun 4.0 software framework (software.sci.utah.edu) to insert realistically shaped ICD cans and electrode leads and manipulate their location by dragging and rotating the objects in a visualization of the torso. This tool was used to generate a database of approximately 350 distinct physical electrode orientations clinical,

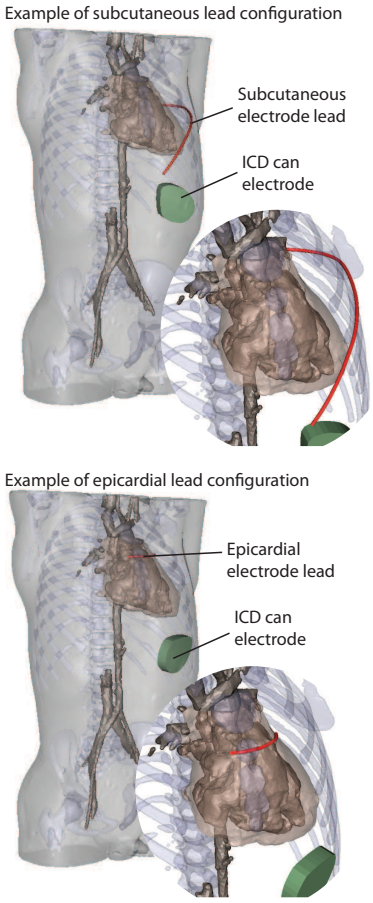


Figure 2. Examples of electrode configurations in a torso of a 10 year old. The red line models the coil of the electrode lead and the green can models the ICD.

which included transvenous, epicardial and subcutaneous electrode lead configurations. The configurations included cases with multiple electrode leads as well as cases with a single electrode lead, also the length of the electrode lead was varied and its proximity to the heart, with epicarial and transvenous leads lying on top of the heart, while the subcutaneous configurations were located further from the heart. Two examples of different electrode configurations are depicted in Figure 2.

### 2.3. Simulation of defibrillation

The electrode configuration and the torso model were combined to predict defibrillation efficacy using the critical mass hypothesis. The latter hypothesis assumes that defibrillation can be achieved by generating an electric field of at least 5 $V/cm$ within at least 95% of the ventricular myocardium. In order to do a relative comparison between different electrode configurations we use a simulation to

estimate the potential that needs to be applied between both leads to fulfill this constraint. This potential is estimated by evaluating a finite element model of the torso for a nominal value of the potential difference and scaling the solution until it meets the critical mass hypothesis. The finite element model needed for this analysis consisted of a locally refined hexahedral mesh that was superimposed on top of the conductivity model and in which each element was assigned a tissue conductivity[2]. The simulation process is depicted in Figure 3. All the simulations were performed within the SCIRun 4.0 software framework.

## 2.4. Conductivity changes

In order to determine the sensitivity to the number of tissue types included in the model we defined a subset lead configurations with approximately 15 representative orientations(5 transveous, 5 epicardial, and 5 subcutaneous) across the 3 torsos, resulting in a total of 47 distinct physical electrode orientations.

For each of these electrode configurations several different volume conductor models were constructed by replacing the conductivity of a certain tissue compartment with the conductivity of the connective tissue. The latter tissue type defined all the structures in the torso that were not included in the segmentation. Hence by replacing the conductivity of those volumes with the conductivity of connective tissue it is effectively taken out of the segmentation.

In order to do a fair comparison we defined the potential difference needed between the leads of the ICD configuration needed to push 95% of the myocardium over 5 $V/cm$ (critical mass hypothesis), as the clinical relevant metric. This metric is the same as used in previous studies[1,2]. In this study this metric is used to compare the full model to the models with a reduced number of tissue compartments.

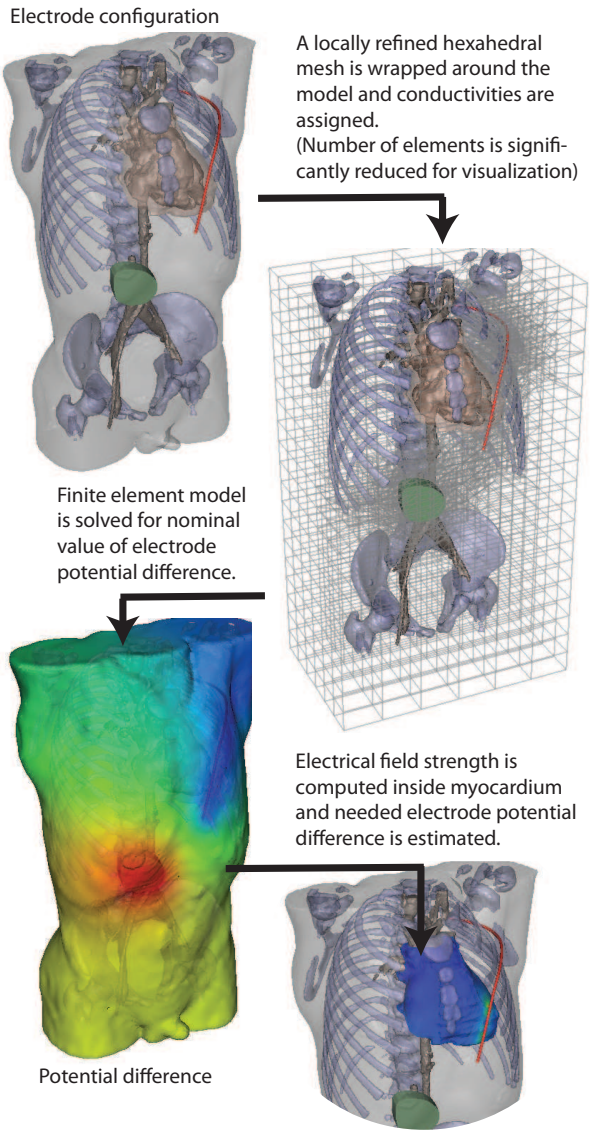


Figure 3. Simulation pipeline for computing defibrillation efficacy.

## 3. Results

In order to determine which tissue types are important for the simulation of defibrillation, two different strategies were employed: (1) in order to estimate the relative contribution of each tissue type, they were sequentially replaced with connective tissue; (2) once the relative contribution of every tissue type was established the most influential tissues types were selected for further evaluation by determining the error made when combining just a few of these influential tissue types.

Table 1 summarizes the results from the first study: it denotes the median and maximum error in predicted defibrillation potentials for both the epicardial, transvenous, subcutaneous cases. The results show that by far blood is the most important tissue to consider, followed by the lungs and the heart itself. However the table shows as well that the presence of bowel gas is important, especially for the subcutaneous cases. The results also show that the bones do not have a large effect on average, however some cases where the leads closely follow a rib, the influence can be considerable as can be seen from the large maximum error. The table shows as well that the kidneys, the muscle tissue and the liver do not alter the predicted defibrillation thresholds dramatically, and hence can be ignored in the model.

We restricted the second part of the analysis to the lungs, blood, heart, bones, bowel gas and fat tissues and simulated almost every combination of these tissue types. To further restrict the number of combinations we assumed

Table 1. Effects of removing one tissue compartment from the model. *epi = epicardial, tv = transveneous sct = subcutaneous

| Omitted tissue type | median rel. error (%) | | | maximum rel. error (%) | | |
|---|---|---|---|---|---|---|
| | epi | tv | subq | epi | tv | subq |
| Blood | 23 | 7.8 | 20 | 42 | 52 | 30 |
| Bone | 1.6 | 4.1 | 2.5 | 23 | 15 | 17 |
| Bowel gas | 4.7 | 5.4 | 9.7 | 45 | 40 | 47 |
| Fat | 7.3 | 3.6 | 4.2 | 12 | 9.1 | 7.7 |
| Heart | 6.8 | 9.6 | 7.0 | 11 | 17 | 11 |
| Kidney | 0.13 | 0.20 | 0.27 | 0.58 | 1.2 | 1.2 |
| Liver | 2.2 | 1.2 | 2.2 | 11 | 4.3 | 8.4 |
| Lungs | 8.5 | 12 | 6.4 | 15 | 25 | 23 |
| Muscle | 2.8 | 1.6 | 1.7 | 5.1 | 5.0 | 4.0 |

Table 2. Effects of adding tissues to segmentation.

| Tissue types in model | median rel. error (%) | | | maximum rel. error (%) | | |
|---|---|---|---|---|---|---|
| | epi | tv | subq | epi | tv | subq |
| heart | 28 | 15 | 41 | 51 | 38 | 57 |
| heart-blood | 15 | 17 | 22 | 43 | 45 | 48 |
| heart-lung | 34 | 12 | 37 | 49 | 59 | 59 |
| heart-blood-lung | 16 | 6.5 | 21 | 47 | 41 | 51 |
| heart-blood-lung-bone | 10 | 6.9 | 15 | 47 | 41 | 51 |
| heart-blood-lung--bone-bowelgas | 6.6 | 2.2 | 3.4 | 14 | 6.1 | 13 |
| heart-blood-lung--bone-fat | 5.4 | 9.5 | 11 | 47 | 40 | 48 |
| heart-blood-lung-bone--bowelgas-fat | 5.2 | 2.1 | 3.2 | 13 | 5.8 | 13 |

that the heart needed to be segmented in any case, as its segmentation is needed to evaluate the critical mass criteria. In Table 2 examples of this second analysis are given. The results show that one preferably wants to have at least the heart, blood vessels, the lungs and the bones in the model. However this combination can still lead to large errors and to restrict the maximum error more variable tissue types like bowel gas may need to be considered.

## 4. Discussion and conclusions

The results presented in this paper show that the optimization of the defibrillation parameters is dependent on the torso volume conductor. The subcutaneous lead configurations, which are clinically are less intrusive, have a larger dependence on the volume conductor, warranting the need for a more detailed model in order to optimize these cases.

The results presented here are currently limited by the accuracy of the critical mass hypothesis. Although this hypothesis is a good start, it ignores many of the intricacies of defibrillation[3]. As the critical mass hypothesis is the most utilized in the translational research literature it was chosen for this analysis.

The simulations show that tissue like liver, kidney, and muscles probably do not need to be modeled and can be ignored in the segmentation, However detailed segmentation of heart, blood volume, lungs, and bones are needed for the patient specific models for both accurate calculations as well as a sufficient reference frame for accurate electrode placement.

Finally, this paper demonstrates the utility of a database of torsos and electrode orientations for large scale analysis of trends in a population. For example, one can easily look at the effect of the varying size of the the gaseous contents of stomach and intestines, which being non-conductive and hence of importance, across many torso models and different orientations. As the amounts vary in patients, one may want to avoid lead configurations that depend too heavily on these tissues. We plan to further develop our database of models and orientations to examine broader trends and relationships such as these.

## Acknowledgements

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