FEASIBILITY OF AND PROGRESS TOWARDS CLINICAL IMPLEMENTATION OF ELECTROCARDIOGRAPHIC IMAGING

by

DAVID CHARLES KAELBER

Submitted in partial fulfillment of the requirements for the degree of Masters of Science

Department of Biomedical Engineering
CASE WESTERN RESERVE UNIVERSITY
May 1994
Copyright © (1994) by

David Charles Kaelber
FEASIBILITY OF AND PROGRESS TOWARDS CLINICAL IMPLEMENTATION OF ELECTROCARDIOGRAPHIC IMAGING

Abstract

by

DAVID CHARLES KAELBER

The so-called inverse problem in electrocardiography involves determining, non-invasively, epicardial potentials and activation isochrones from measured body surface potentials. For many years researchers and clinicians have searched and longed for a non-invasive method to image the electrical activity of the heart, which solutions to the inverse problem in electrocardiology would provide. Over the years, much theoretical work and clinical progress has been made toward determining epicardial potentials in this manner, although actual inverse solutions in humans have not, as yet, been reproduced with sufficient accuracy to be usable clinically. This thesis broadly identifies the steps left to make electrocardiographic imaging a clinical reality, and then specifically addresses advancements in \textit{in vivo} geometrical determinations, needed to make this new imaging technique possible. Clinical procedures coupling body surface potential mapping (BSPM) with computer tomography (CT) yielded body surface and epicardial geometries, as well as BSPM electrode position, in six (6) healthy volunteers, accurately and reproducibly. As part of these procedures, CT scans localized electrode position on the body surface with a 224-electrode BSPM vest.
Preface

Deciding to pursue any career, and particularly a career in scientific research, is deciding to devote your life to a particular pursuit. My MS degree has been my first major step along that path. Throughout my last three years at Case Western Reserve University I have explored pursuing a lifetime career of research in biomedical engineering and I have learned much.

During these three years I have seen that devoting your life to research means committing yourself to the search for answers to the questions and problems which you choose to tackle. This quest can be very exciting and fulfilling, but also sometimes isolating. The skills needed for this endeavor cannot be learned by reading about them or listening to others talk about them, but only through personal experience and sometimes struggle.

As I begin to focus on continuing to obtain my PhD and pursuing a life committed to scientific research, all the lessons I have learned and people I have watched and tried to model myself after should provide an invaluable resource. For me, this time has also been a time of learning to focus and trying to prioritize what is most important in my life. I appreciate the patience and understanding with which those whom I have worked with have dealt with me.

“The best use of life is to spend it for something that outlasts life.”

--William James
Acknowledgments

Completion of this project would not have been possible without the help of numerous individuals. I would like to particularly thank the following people: David Bregman, John Burnes, Ann Donohoo, Rennie Fraenkel, Bonnie Hammie, Dirar Khoury, Ken Laurita, Dr. Kyoung Jung Lee, Dr. Jerome Liebman, Gary Muswick, Dr. Dennis Nelson, Howie Oster, Leora Peltz, Robert Steagall, JoAnn Uline, Sue Lockshine, the staff of the Department of Radiology at University Hospitals of Cleveland, my research subjects, my research advisor, Dr. Yoram Rudy, the rest of my MS committee, Dr. John Haaga, Dr. Cecil Thomas, and Dr. Albert Waldo, and for moral support, Robin Shaw. Any questions I had or problems I encountered, they were always willing to listen to me and support me. My work is built upon their foundations and only with their help. Thank you.

My training and this work was support by NIH Training Grant 5-T32-GM-07535-16, as well as NIH National Heart, Lung, and Blood Institute Grant 33343.
# Table of Contents

Abstract ................................................................. i  
Preface .............................................................................. ii  
Acknowledgments ......................................................... iii  
Table of Contents .......................................................... iv  
Table of Figures ............................................................... vii  

## Chapter 1 - Introduction to Electrocardiographic Imaging

1.1 Introduction to Electrocardiographic Imaging .......... 2  
1.2 Introduction to the Body Surface to Epicardium Inverse Problem in Electrocardiography .......... 5  
1.3 Filter Model ............................................................... 6  
1.4 Theoretical Developments in the Inverse Problem .......... 7  
1.5 Tank Torso Work ........................................................ 9  
1.6 Geometrical Problem Definition ................................. 11  
Endnotes ........................................................................... 12  

## Chapter 2 - Clinical Determination of Body Surface and Epicardial Geometries for Electrocardiographic Imaging

(This chapter was presented in a 2-page paper to the IEEE-EMBS 16th Annual International Conference, Baltimore MD, November 3-6, 1994 (Appendix - A)) .......... 14  
2.1 Introduction ............................................................... 15
**Table of Figures**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Inverse problems with specific references to electrocardiography.</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Low-pass filter model of electrocardiographic imaging.</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Protocol used for in vivo study.</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Enhanced representative transverse CT slice.</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Anterior coronal slice of identified electrodes with electrode numbers.</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Actual electrode position in anterior portion of vest laying flat.</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Posterior coronal slice of identified electrodes with electrode numbers.</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Actual electrode position in posterior portion of vest laying flat.</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Two views the body surface geometry created by the body surface matrix. The vertices of each triangle indicate electrode position.</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Two views of the epicardial envelope created by the epicardial matrix.</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Two views of the epicardial envelope within the body surface geometry.</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Sample of body surface with potentials overlaid analogous to display of epicardial envelope with potentials overlaid.</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction to Electrocardiographic Imaging

1.1 Introduction to Electrocardiographic Imaging
1.2 Introduction of the Body Surface to Epicardium
   Inverse Problem in Electrocardiography
1.3 Filter Model
1.4 Theoretical Developments in the Inverse Problem
1.5 Tank Torso Work
1.6 Geometrical Problem Definition
1.1 Introduction to Electrocardiographic Imaging

Heart disease is the number one killer of adults in the United States. Currently, heart disease causes over 33% of all deaths, regardless of age, for a total of over 720,000 deaths per year [1]. Although, the heart's electrical system does not play a role in all of these deaths, conduction abnormalities, specifically sudden death from arrhythmias, play a very significant role in people's lives. For example, currently, over 460,000 pacemakers are implanted annually [2] and over 3,000 people suffer from myocardial infarctions daily [3].

The first step in addressing this pressing medical problem involves developing methods to image cardiac electrical activity, termed electrocardiographic imaging. These imaging techniques serve to provide health professionals with detailed information about normal and abnormal cardiac electrical activity. In terms of diagnostic information, these techniques can provide information ranging from gross activation sequences, to characterizing ischemic and infarcted cardiac regions, to localizing ectopic foci and accessory pathways in Wolff-Parkinson-White syndrome. In addition to diagnostic information, electrocardiographic imaging can also serve a valuable role in the development and evaluation of drug and surgical therapies to address cardiac electrical abnormalities. From a research perspective this imaging field can furnish basic information about arrhythmias and fibrillation. Overall, electrocardiographic imaging strives to provide health professionals with detailed information about the electrical activity of the heart.
Currently health professionals and researchers use many different types of electrocardiographic imaging techniques including the EKG (electrocardiogram), vectorcardiography, body surface potential mapping (BSPM) [4]-[5], epicardial mapping [6], transmural cardiac mapping [7], and endocardial mapping [8]-[9], to help image the heart’s electrical activity. A new, emerging electrocardiographic imaging approach, known at the inverse problem in electrocardiography, involves reconstructing potentials close to the heart from potentials measured further from the heart.

This type of electrocardiographic imaging approach takes two forms. First of all, body surface potentials can be used to compute epicardial potentials. Also, intra-atrial and intra-ventricular potentials can be used to compute endocardial potentials. This imaging avenue provides several advantages over other electrocardiographic imaging techniques for detailed, non-invasive mapping of the electrical activity of the heart.

Clinically used electrocardiographic imaging techniques currently fall into one of two categories. Either they measure body surface potentials non-invasively (EKG, vectorcardiography, BSPM), or they measure actual cardiac potentials invasively (epicardial, transmural, and endocardial mapping). The disadvantage of the first approach arises from the fact that differing body tissue conductivities non-uniformly dampen the electrical signals from the heart as they travel to the body surface. Therefore, the measured body surface potentials differ from the actual cardiac potentials in a non-trivial way. Even if the body cavity were a homogeneous volume conductor, it would still dampen the epicardial signals,
causing a loss of resolution on the body surface, as compared to the epicardium. The major drawback to the second set of electrocardiographic imaging methods comes from their invasive nature. Epicardial, transmural, and endocardial mapping all require direct access to the surface of the heart. Electrocardiographic imaging, through inverse solutions, overcomes the disadvantages of both of the previously existing groups of electrocardiographic imaging techniques by providing an accurate estimate of actual cardiac potentials, non-invasively.

Within this framework, this work focuses on the process of bringing electrocardiographic imaging through body surface to epicardium inverse solution methodology into the clinical setting. The specific aims of this work are three-fold, as follows:

1) to present work done in inverse problem electrocardiographic imaging leading up to clinical implementation of inverse problem solutions;

2) to develop and present a methodology to determine body surface (electrode) and epicardial geometries, in relationship to each other, non-invasively;

3) to present the final steps needed to make electrocardiographic imaging through inverse solutions a clinical reality.
1.2 Introduction to the Body Surface to Epicardium Inverse Problem in Electrocardiography

Electrocardiographic imaging, as embodied by the body surface to epicardium inverse problem approach, has long been pursued as a key non-invasive cardiac imaging tool [10],[11],[12],[13],[14],[15],[16],[17],[18]. Through this approach, potentials measured far away for a source(s) are used to compute potentials closer to the source(s). In electrocardiographic imaging, myocardial tissue contains the source(s), so that the body surface is the surface far removed from the source(s) and the epicardium is the surface close to the source(s) (Figure 1).

Clinical needs, as well as mathematical formulation, help determine the most clinically useful format for the inverse computed solutions. For instance, the inverse approach could be used to determine equivalent intracardiac sources.

Figure 1 - Inverse problems with specific references to electrocardiography.
(monopoles, dipoles, quadropoles, etc.). However, this information is not very useful clinically because equivalent sources have no physiological meaning. Also, these solutions are not unique, as many different intracardiac source configurations lead to the same body surface potentials. From the clinical prospective, potentials and isochrones on an envelope surrounding the epicardium provide the most useful information. These solutions are unique. In addition, they correlate well with the underlying electrical activity. The potential information provides a snap-shot of the cardiac voltage distribution at an instant in time. Isochrones, by identifying regions of the heart which activate at the same time, indicate the overall activation sequence of the heart during the cardiac cycle.

1.3 Filter Model

From a purely systems and electrical engineering perspective electrocardiographic imaging through the body surface to epicardium inverse problem can be viewed as a time-invariant filter system problem (Figure 2). In this view, the body acts as a time-invariant, low-pass filter with the input being the epicardial potentials and the output being the body surface potentials.

Therefore, to determine the epicardial potentials, measure the body surface potentials and couple this information with the low-pass transfer function of the body. Take the inverse of the transfer function and convolve it with the output (epicardial potentials) to determine the input (body surface potentials). The transfer function is characterized by the anatomical distances and conductivity
(given a non-homogeneous medium) between the body surface and the epicardium.

1.4 Theoretical Developments in the Inverse Problem

The theoretical basis for the inverse problem comes from Green’s Second Theorem,

\[ \int_{S} (A\nabla B - B\nabla A) \cdot \hat{n} \, dS = \int_{V} (A\nabla^2 B - B\nabla^2 A) \cdot dV. \]

Derived from this mathematical statement comes the analysis that given the value for a function on a certain surface far away from the source(s), the value for the function on a surface closer to the source(s) can be determined. This can be expressed mathematically as \( V_f = AV_n \), where \( V_f \) is a matrix of potential functions far away from a source configuration, \( V_n \) is a matrix of potential functions near a source configuration, and \( A \) is a matrix of functions relating the two. If a
homogeneous medium exists between surfaces of \( V_f \) and \( V_n \), then \( A \) contains only geometrical information. If a non-homogeneous medium exists between surfaces \( V_f \) and \( V_n \), then \( A \) contains conductivity information, as well as geometrical information. In the case of the body surface to epicardium inverse problem, \( V_f \) denotes body surface or torso voltage functions, \( V_n \) denotes epicardial voltage functions, and \( A \) characterizes the tissue between these two surfaces.

Given the mathematical formulation, \( V_f = AV_n \), body surface potentials can readily be computed from epicardial potentials. This is considered the forward problem. To compute epicardial potentials from body surface potentials, the inverse problem, the matrix \( A \) must be inverted so that \( V_n = A^{-1}V_f \). Unfortunately, the \( A \) matrix is ill-conditioned (has a large condition number; i.e. widely differing eigenvalues) so the inverse problem in electrocardiography is a mathematically ill-posed problem and the matrix \( A \) cannot be inverted directly. Being ill-posed means that mathematically, the formulation of inverse solutions is inherently unstable. Therefore, small errors in input information, such as low-level noise or small errors in geometry, are magnified to produce large errors in computed epicardial potentials. To address this problem various regularization schemes constrain epicardial potential solutions.

Mathematically, to address this regularization issue \( V_f = AV_n \) or

\[
V_{\text{body surface}} = A V_{\text{epicardial}},
\]  

(1)
is transformed into

\[ V_{\text{epicardial}} = \min_{V_{\text{epicardial}}} \left[ \| A V_{\text{epicardial}} - V_{\text{torso}} \|^2 + f(V_{\text{epicardial}}) \right] \]  

(2)

The first term in this second equation (2) represents the least squares solution to \( V_{\text{epicardial}} \) in the first equation. The second term in the second equation corresponds to the regularization term. Regularization schemes used to date generally fall into one of two categories - 1) Tikhonov regularization and 2) Twomey regularization. Tikhonov regularization places constraints on the amplitude of the solution (zero order), the gradient of the solution (first order), the Laplacian of the solution (second order), etc. Twomey regularization uses \textit{a priori} information about the solution. This technique can incorporate information known about the spatial and temporal distribution of expected epicardial potentials. By placing constraints on the inverse solutions these regularization techniques stabilize the solutions.

### 1.5 Tank Torso Work

Although the first work in developing inverse problem methodology occurred in simulated eccentric spheres models, the need arose to develop a more realistic \textit{in vitro} model for study. Only in this way could the next steps be taken to prepare this new imaging technology for \textit{in vivo} study. Tank torso studies provide this vehicle.
Tank torso studies involve a torso mold filled with electrolytic media into which a dog heart is placed. In this situation, electrode rods and electrode socks can readily record potential measurement on the torso mold surface, throughout the electrolytic media, and on the epicardium. Also, the exact geometrical position of the torso and heart can be measured. Therefore, estimated epicardial potentials can be computed from body surface potentials and compared to measured epicardial potentials. The tank torso model provides the ideal situation in which to verify and enhance inverse solution techniques in preparation for clinical trials.

In this experimental setup, work has progressed to the point where potential features during normal sinus rhythm (i.e., maxima and minima) can be reconstructed with good accuracy (typically within 1.5cm of their actual epicardial position) [19]. Additionally, pacing sites simulating arrhythmogenic foci have been located with similar accuracy. Dual simultaneous pacing sites 2cm apart were also resolved [20]. These studies demonstrate the value of the tank torso model and indicate that the groundwork has been laid to take the next step toward clinical implementation of inverse problem solutions.
1.6 Geometrical Problem Definition

The critical step needed to make electrocardiographic imaging through inverse reconstruction a viable clinical possibility, involves being able to determine the location of the body surface and epicardium non-invasively. In model and tank torso constructions the “body” surface and “heart” surface are experimentally defined and, therefore easy to measure. These conditions do not exist in bringing this technique into humans, where the body surface and heart surface are not fixed and not easily determined.

With this background into electrocardiographic imaging, the focus turns to clinical implementation issues. The next chapter focuses on a technique developed to determine the needed body surface and epicardial geometries. The final chapter addresses several other practical clinical implementation issues needed to make electrocardiographic imaging through body surface to epicardium inverse reconstructions clinically practical.
**Endnotes**


Chapter 2

Clinical Determination of Body Surface and Epicardial Geometries for Electrocardiographic Imaging

(an in vivo study)

2.1 Introduction
2.2 Methods
2.3 Results
2.4 Discussion
2.1 Introduction

To make electrocardiographic imaging a clinical reality a relatively inexpensive, accurate, quick, easy, and reproducible procedure for determining body surface (electrode) and epicardial geometries needs to be determined. A procedure using CT (computer tomography) meets these criteria. Taking a CT scan of a subject while wearing a body surface potential map (BSPM) vest, clearly identifies the electrode positions on the surface of the body and the position of the epicardial envelope (a surface close to the epicardium) with respect to each other, in each CT slice. This CT scan information allows determination of body surface and epicardial geometries. These geometries, coupled with BSPM data enable computation of epicardial potentials through inverse reconstructions. A six subject in vivo study helped develop, refine, and validate this technique to determine 3-dimensional body surface and epicardial envelope geometrical matrices relative to each other. This method could be readily applied to identify other tissue layers of interest as well, or could be used with other imaging modalities (MRI, ultrasound, etc.).

2.2 Methods

Each normal, healthy volunteer subject underwent both a CT scan with a 224 lead body surface potential map (BSPM) vest on. The CT scans were taken on the Siemens Somatom Plus spiral CT scanner of the Humphrey CT unit at University Hospitals of Cleveland. Each scan used 8mm contiguous slices over the area of the vest, so that all 224 BSPM vest electrodes appeared in the field of view. The
complete scan encompassed two or three individual scans, depending on the subject. During the scan, the breathing protocol consisted of instructing the subject to inhale deeply, exhale, inhale deeply, and hold it. Scans were taken during the breath hold. A plastic water vessel also rested on the subject's chest on top of the vest to ensure good electrode contact anteriorly. A copy of the complete protocol and a blank subject information sheet occurs in Figure 3 and Appendix B respectively.

The CT data were transferred via reel-to-reel tape to SUN SPARCstations for analysis in 16 bit signed Little Endian format (Appendix C). To analyze the CT data a software package, Digital Image Processing (DIP) Station [1], allowed pixel coordinate identification via human selection. Point of interest (POI) pixel identification for the BSPM vest electrodes occurred for the body surface. Point of interest pixel identification took place based on the bright CT artifacts caused by the Ag/AgCl BSPM electrodes. Region of interest (ROI) pixel identification marked the epicardial envelope coordinates. In-slice epicardial region of interest analysis occurred based on the clearly discernible difference between the density of cardiac tissue (myocardial and pericardial tissue) and the surrounding lung tissue. Transverse slice selection occurred superiorly based on bifurcation of the trachea and inferiorly based on diaphragm/liver localization.
Inverse and Forward Problems in Electrocardiography

Subject Protocol

Goal
To take one volunteer with a body surface potential map (BSPM) vest on and obtain a CT of the area covered by the BSPM vest using the spiral CT scanner.

Protocol
1) Place the BSPM vest on the subject (have the subject raise their arms BEFORE final vest placement; place water weights on subject's chest).
2) Proceed with either the BSPM recording or the CT scan (see below for details).
3) After the procedure is completed, take the vest off the subject.
4) Measure the location of the 12 points (6 in front and 6 in back) in reference to anatomical markers.
5) When ready to proceed with the next procedure, first locate and mark the 12 points on the body.
6) Place the BSPM vest on the body using these 12 reference points (have the subject raise their arms BEFORE final vest placement; place water weights on subject's chest).
7) Proceed with either the BSPM recording or CT scan (see below for details).

BSPM Recording Details
1) Raise the subjects' arms above/behind their head.
2) To regulate breathing, before data acquisition, ask the subject the breath deeply, exhale, breath deeply again, and hold. Acquire data during the hold.

CT Scan Details
1) Place the subject, with the BSPM vest on, in the spiral CT scanner. Raise the subject's arms above/behind their head.
2) Take scout CT scan to determine vest position.
3) To regulate breathing, before data acquisition, ask the subject the breath deeply, exhale, breath deeply again, and hold. Acquire data during the hold.
4) Take CT scan, as indicated above, using the following criteria:
   a) 8mm thick contiguous slices.
   b) Note magnification factor.
   c) Make hard copy of images.
   d) Save the 512x512 (not briefed, not compressed) data of the CT scan to tape.

Record all information on the Subject Information Sheet

Figure 3 - Protocol used for in vivo study.
After point of interest and region of interest analysis occurred, a second, self-written program (Appendix D) converted the POI (body surface) and ROI (epicardial envelope) pixel coordinates into metric measurements of x, y, and z, shifted coordinates relative to a local zero, and meshed each 2-dimensional slice into two 3-dimensional slices, one containing the body surface (electrode) geometrical matrix and one containing the epicardial envelope geometrical matrix. For the POI analysis, this program also contained error analysis algorithms to verify selection of each electrode and that each electrode occurred in its relative position based on its neighbor electrodes, as indicated in the neighbor table (Appendix E). Finally, this program enabled the triangularization of the body surface and epicardium needed for computation of epicardial potentials for inverse solutions, through numerical integration, using boundary element methods. For the body surface, the program places electrodes in numerical order to allow easy triangularization using the triangle mesh table (Appendix F). For the epicardium, automatic rectangular triangularization occurs based on a user selected number of points from each ROI CT slice.

Either before or after the CT scan, BSPM recording occurred. When the vest was removed from the subject for the first time, detailed measurements of six anterior and six posterior electrodes were made using a standard clothier's tape measure. To place the vest on the subject again, these 12 points were first placed on the body using a dry erase marker. Then the vest was placed relative to these points.
2.3 Results

The goal of the results of the in vivo study consists of developing a reproducible method to construct 3-dimensional body surface and epicardial geometrical matrices. Of the six subjects who underwent the procedures described above, complete data analysis of one subject is shown below. Representative results appear below and are organized in two sections - intermediate and final results. Intermediate results include a typical CT scan slice, anterior and posterior coronal views of electrodes, and the output coordinate formats of DIP station for one POI and one ROI slice (Appendix G and Appendix H). Final results include the 3-dimensional body surface and epicardial geometrical matrices (Appendix I and Appendix J), as well as meshes of these matrices.

In terms of intermediate results, three figures appear. Figure 4 shows a typical CT scan slice. The subject is supine with the BSPM vest on and a water container placed on top of it to ensure good vest contact anteriorly on the chest, without degrading the CT image. The body surface, epicardium, lungs, body cavity, and electrodes are indicated. The electrodes, surfaces of interest (torso and epicardium), as well as other tissues such as the lungs, are clearly visible even without enhancement. Figure 5 shows an anterior coronal slice of identified electrodes compared to actual electrode position in Figure 6. The actual electrode
position figure indicates the electrode position when the vest is laying flat, so this should differ from the measure electrode position when the vest is on the body, particularly laterally, where the vest follows the body contour. Given this, the electrodes generally match the vest design (Appendix K).

Figure 4 - Enhanced representative transverse CT slice.
Figure 5 - Anterior coronal slice of identified electrodes with electrode numbers.

<table>
<thead>
<tr>
<th>28</th>
<th>34</th>
<th></th>
<th>56</th>
<th>64</th>
<th>66</th>
</tr>
</thead>
<tbody>
<tr>
<td>66</td>
<td>49</td>
<td>50</td>
<td>73</td>
<td>69</td>
<td>65</td>
</tr>
<tr>
<td>74</td>
<td>44</td>
<td>66</td>
<td>70</td>
<td>67</td>
<td>65</td>
</tr>
<tr>
<td>58</td>
<td>43</td>
<td>67</td>
<td>99</td>
<td>61</td>
<td>62</td>
</tr>
<tr>
<td>76</td>
<td>44</td>
<td>68</td>
<td>80</td>
<td>00</td>
<td>06</td>
</tr>
<tr>
<td>61</td>
<td>62</td>
<td>63</td>
<td>115</td>
<td>127</td>
<td>131</td>
</tr>
</tbody>
</table>

Figure 6 - Actual electrode position in anterior portion of vest laying flat.
Figure 7 shows a posterior coronal slice of identified electrodes. Here again, particularly taking into account that the actual electrode position is taken when the vest is laying open and flat, these pictures correspond very well with the actual electrode position in Figure 8 and vest design (Appendix K).

The final results of the *in vivo* procedure arise in two figures. Figure 9 shows the geometrical body surface/torso matrix and Figure 10 shows the epicardial matrixes of one subject. Figure 11 exemplifies the epicardial envelope within the body surface created by the geometrical matrices of one subject.
Figure 7 - Posterior coronal slice of identified electrodes with electrode numbers.

Figure 8 - Actual electrode position in posterior portion of vest laying flat.
Figure 9 - Two views the body surface geometry created by the body surface matrix. The vertices of each triangle indicate electrode position.
Figure 10 - Two views of the epicardial envelope created by the epicardial matrix.
Figure 11 - Two views of the epicardial envelope within the body surface geometry.
2.4 Discussion

In the overall evaluation of the technique used, two overriding points should be clear. First, this technique works as a method to provide body surface and epicardial geometries needed for electrocardiographic imaging through inverse solutions. Secondly, the technique described has various sources of potential errors associated with it.

This technique allowed determination of all 224 BSPM electrodes on the body surface. Qualitatively, electrodes appeared relative to each other spatially in the vest. Also, the epicardial envelope generally mimics expected cardiac morphology and appears in a position expected in the thoracic cavity. The epicardium appears anteriorly, on the left lateral position of the chest cavity, slightly tilted medially. The heart appears slightly enlarged and squashed probably because of errors in clearly identifying the base and apex of the heart, errors clearly distinguishing myocardial tissue from the surrounding pericardium, and errors caused by CT slice thickness. Quantitatively, accuracy of electrode position is on the order of 1-2mm in the transverse (in-slice) direction and on the order of 8mm (CT slice thickness) or greater in the sagittal direction. Similarly, epicardial accuracy is on the order of 1cm both the transverse (in-slice) and sagittal directions, due to CT slice thickness and cardiac motion.

Within the overall success of this approach, the main possible source of error revolves around limitations associated with the CT hardware. First of all, each CT scan takes approximately 1 second to acquire, or about 40 seconds for an
entire scan, many cardiac cycles. This cardiac motion causes blurring of the heart-lung interface [2]. This potential error source could be overcome through the use of non-mechanical rotating CT scanners. Given that the entire CT scan encompasses at least two breath holds, errors might also be introduced in the lack of reproducibility of the breath hold protocol, although the protocol used is generally taken as reproducible [3]. Another source of error involves the thickness of each CT slice. Each CT slice spans 8mm, so that the maximum transverse resolution is 8mm. Also, this slice thickness hinders identification of BSPM electrodes spanning multiple slices. This limitation could be improved with smaller electrodes or preferably smaller slice thickness during the CT scan. Another imaging modality could also be examined which overcomes some of these limitations associated with CT, such as MRI.

CT analysis serves as a viable approach to determine body surface (and BSPM electrode), as well as epicardial envelope geometry non-invasively. The geometrical information determined via this method should provide adequate geometrical information to compute inverse problem solutions.
Endnotes


3. Personal correspondence with Dr. John Haaga, Chair, Department of Radiology. University Hospitals of Cleveland. 1994.
Chapter 3

Future Directions in Electrocardiographic Imaging

3.1 Introduction
3.2 Body Surface Potential Mapping Issues
3.3 Tissue Conductivity Issues
3.4 Computational Issues
3.5 Display Issues
3.6 Conclusions
3.1 Introduction

Bridging the gap to bring a theoretical technology into a clinical setting requires many steps in addition to the theoretical issues involved. Developing viable clinical electrocardiographic mapping through inverse problem solutions requires addressing many practical issues. Determining the body surface and epicardial geometries marks the completion of one vital part of this process.

As indicated in Chapter 1, at least three (and possibly four) pieces of information need to be determined to compute epicardial potentials from body surface potentials. These pieces of information include the following:

1) body surface geometry
2) body surface potential information
3) epicardial geometry
4) tissue conductivities (if multiple tissue layers are to be included; i.e., non-homogeneous media)

Noninvasive determination of body surface and epicardial geometry, as discussed in the previous chapter, provides two of the pieces of information needed. The following sections discuss additional issues involved in bringing this new type of electrocardiographic imaging technique into the clinical setting.

3.2 Body Surface Potential Mapping Issues
To obtain body surface potentials, a viable body surface potential mapping (BSPM) system needs to be in place. Such a system exists at University Hospitals of Cleveland. The electronics of the system allow up to 224 channel inputs at sampling speeds of 500, 1000, and 2000 Hz for recording lengths of up to 45 minutes. Sampling rates, as well as filtering can be controlled via software [1-2].

Given the electronics of the BSPM system, various electrode vests plug into the front end of the BSPM electronic hardware to provide input signals. Currently, one 224 electrode vest exists. The vest uses 5 mm diameter Ag/AgCl electrodes in a rubber/Velcro mesh suitable for use on a somewhat wide range of adult males. For complete electrocardiographic imaging in this manner, a host of vests to fit a wide range of patient type (males, females, adults, children, obese, slender, etc.) need to be developed.

In addition to hardware issues related to BSPM creation, a theoretical issue arises as well. For the inverse solution to be computed, Greens’ Second Theorem dictates that closed surfaces be used. However, the BSPM system only acquires data over the anterior and posterior thoracic surfaces. The system obtains no data of potential and/or current distributions through the arms, head, or legs. Some account needs to be made for this information. Also, in terms of the epicardium, some mechanism needs to be developed to close off the cardiac surface, inferiorly and particularly superiorly.
3.3 Tissue Conductivity Issues

Another critical variable in determining epicardial potentials from torso potential revolves around determination of tissue conductivities. Tissue conductivities become essential to model the thoracic cavity (body surface to epicardium) as more than one continuous tissue layer. Several approaches can be taken to address this issue.

As a first approximation, the thoracic cavity can be modeled as one homogeneous tissue layer, in which case tissue conductivity does not appear in the mathematical formulation. A more accurate approach would involve using standard values for the tissue conductivities of important layers, particularly the lungs. The most accurate approach would involve determining unique tissue conductivities for each patient either via impedance mapping [3] or biopsy needle insertion [4].

3.4 Computational Issues

Computers play a vital role in data analysis and display in electrocardiographic imaging. Given solutions to all the other practical issues, ideally clinicians will have access to body surface to epicardium inverse solutions in near real-time and
with minimal effort on their part. Only recently has computer technology begun to reach a stage where these two goals becomes realistic.

To readily accomplish these two goals of real-time analysis and minimal human intervention both software and hardware issues need to be addressed. Computational methods need to be improved and maximized to make the best use of present and developing workstation technology for near real-time analysis to be possible. Also, inverse solution software must become more “black box” like for wide clinical application. This criteria would make the inverse software easily usable by health professionals unfamiliar with all the mathematical and computational issues needed to compute estimated epicardial potentials from body surface potentials.
3.5 Display Issues

To make electrocardiographic imaging through body surface to epicardium inverse solutions a viable clinical reality, display formats must be developed for health professionals which provide the information they need in an efficient and user-friendly manner. Three dimensional color maps isochrone and potential maps fulfill these criteria. Methodology was developed to display body surface potential maps in conjunction with the commercial software package Tecplot on SUN workstations (Figure 12).

Figure 12 - Sample of body surface with potentials overlaid analogous to display of epicardial envelope with potentials overlaid.
Current BSPM display methodology includes techniques for bad electrode detection and correction, elimination of DC drift, and voltage potential interpolation between electrodes. Similar display formats need to be developed for epicardial potentials and isochrones.

3.6 Conclusions

Throughout this section the elements needed for clinical electrocardiographic imaging through inverse solutions have been presented. Although some of the pieces require further development all the basics exists - body surface potential information, body surface and epicardial geometries, and inverse software and display. Therefore, the next steps involve beginning limited in vivo studies while further addressing, in tandem, the areas mentioned above. In the near future body surface to epicardium inverse procedure reconstructions will be attempted on approximately 5 to 10 patients from any of the following cohorts: 1) Wolff-Parkinson-White (WPW) syndrome; 2) ventricular epicardial pacing (epicardial pacing wires); 3) ventricular endocardial pacing (pacemakers); 4) right bundle branch block (RBBB) and left bundle branch block (LBBB); and 5) normal sinus rhythm.
The work presented here on electrocardiographic imaging embodied in body surface to epicardium potentials represents a small contribution in a long line of previous scientific advancement in this area. However, this is one step closer to making this new imaging technology a clinical reality.
Endnotes


4. Personal correspondence with Dr. John Haaga, Chair, Department of Radiology. University Hospitals of Cleveland. 1993

Literature Cited


Oster HS. *Electrocardiographic Imaging: Non-invasive Localization of Arrhythmogenic Sites of the Heart.* lecture to the Department of Biomedical Engineering at Case Western Reserve University. April 19, 1994.


Appendix A - 2-Page Paper Submitted to IEEE/EMBS 16th Annual International Conference, Baltimore MD, November 3-6, 1994
NON-INVASIVE *IN VIVO* DETERMINATION OF BODY SURFACE AND EPICARDIAL GEOMETRIES FOR ELECTROCARDIOGRAPHIC IMAGING

David Kaelber, MS, John Haaga, MD, and Yoram Rudy, PhD
Department of Biomedical Engineering, Case Western Reserve University, Cleveland OH 44106

**ABSTRACT** - The inverse problem in electrocardiography involves determining, non-invasively, epicardial potentials and activation isochrones from measured body surface potentials [1][2][3]. Although much theoretical work and some preliminary clinical work has been done in this area, one major obstacle to bringing this technique into the clinical arena involves determining, non-invasively, body surface and epicardial surface geometry. Clinical procedures coupling body surface potential mapping (BSPM) with computer tomography (CT) yielded body surface and epicardial geometries, as well as BSPM electrode position, in six (6) healthy volunteers, accurately and reproducibly. As part of these procedures, CT scans localized electrode position on the body surface of a 224 electrode BSPM vest.

**KEYWORDS** - body surface potential mapping, computer tomography (CT), electrocardiographic imaging, inverse problem.

**INTRODUCTION**
To make electrocardiographic imaging through inverse problem solutions a clinical reality a relatively inexpensive, accurate, quick, easy, and reproducible procedure for determining body surface (electrode) and epicardial geometries needs to be developed. A procedure using CT (computer tomography) meets these criteria. Taking a CT scan of a subject while wearing a body surface potential map (BSPM) vest, clearly identified the electrode positions on the surface of the body and the position of the epicardial envelope (a surface close to the epicardium) with respect to each other, in each CT slice. This CT scan information allows determination of body surface and epicardial geometries. Coupled with BSPM data, the geometries enable computation of epicardial potentials through inverse reconstructions. This method could be readily applied to identify other tissue inhomogeneities (e.g. lungs), as well.

**METHODS**
Each normal, healthy volunteer subject underwent a CT scan with a 224 lead BSPM vest on. The CT scans were taken on a Siemens Somatom Plus spiral CT scanner of the Humphrey CT unit at University Hospitals of Cleveland, using 8mm contiguous slices over the area of the vest, so that all 224 BSPM vest electrodes appeared in the field of view. During the scan, the subject was supine, breathing was controlled, and a plastic water vessel rested on the subject's chest, above the vest, to ensure anterior contact without sacrificing image quality.

To analyze the CT data, Digital Image Processing (DIP) Station, an image processing software package, allowed pixel coordinate identification via human selection. Point of interest (POI) pixel identification for the BSPM vest electrodes was performed on the body surface, based on the bright CT artifacts caused by the Ag/AgCl BSPM electrodes. Region of interest (ROI) pixel identification marked the epicardial envelope coordinates. In-slice epicardial ROI analysis was determined based on the clearly discernible difference between the density of cardiac tissue (myocardial and pericardial tissue) and the surrounding lung tissue. Transverse slice selection was determined superiorly based on bifurcation of the trachea and inferiorly based on diaphragm/liver localization.

After conducting POI and ROI analysis, a second, self-written program converted the POI (body surface) and ROI (epicardial envelope) pixel coordinates into metric measurements of x, y, and z. This program also shifted coordinates relative to a local origin, and meshed each 2-dimensional slice into two 3-dimensional groups, one containing the body surface (electrode) geometrical matrix and one containing the epicardial envelope geometrical matrix.

**RESULTS**
The goal of this in vivo study is to develop a reproducible method to construct 3-dimensional body surface and epicardial surface geometrical matrices. Figure 1 shows a typical CT scan slice. The electrodes, surfaces of interest

![Figure 1 - Representative transverse CT scan.](image-url)
Reconstructed                             Actual Figure 2 - Reconstructed (molded to body) and actual (flat) anterior electrode location.

Reconstructed                             Actual Figure 3 - Reconstructed (molded to body) and actual (flat) posterior electrode location.

Figure 4 - Two views of a reconstructed epicardial envelope matrix in a reconstructed torso matrix. (torso and epicardium), as well as other tissue (e.g. lungs), are clearly visible even without enhancement. Figure 2 shows an anterior coronal slice of identified electrodes compared to the actual anterior vest blueprint. Figure 3 shows a posterior coronal slice of identified electrodes compared to the actual posterior vest blueprint. Figure 4 shows two views of a reconstructed epicardial envelope in a reconstructed torso.

DISCUSSION
Results demonstrate the feasibility of this approach for determining, non-invasively, body surface and epicardial geometries, as well as electrode position, for the purpose of clinical electrocardiographic imaging. Sources of potential error are discussed below. This technique allowed determination of all 224 BSPM electrodes on the body surface. Qualitatively, electrodes were reconstructed in a spatial matrix that duplicated correctly their arrangement in the BSPM vest.

Also, the epicardial envelope is clearly defined in the CT scan. Quantitatively, accuracy of electrode position is estimated to be on the order of 1-2mm in the transverse direction and on the order of 8mm (CT slice thickness) in the coronal plane.

Within the overall success of this approach, the main possible source of error revolves around limitations associated with the CT scanner. First, each CT scan takes on the order of 1 second to acquire, or about 40 seconds for an entire scan (many cardiac cycles). Cardiac motion causes blurring of the heart-lung interface [4]. However, the region surrounding the heart is clearly defined and provides an "epicardial envelope" for the inverse reconstruction of potentials. This potential error source could be overcome through the use a of non-mechanically rotating CT scanner. Given that the entire CT scan encompasses at least two breath holds, errors might also be introduced in the lack of reproducibility of the breath hold protocol, although the protocol used is generally known as reproducible. Another possible source of error involves the thickness of each CT slice. The 8mm slice thickness hinders identification of BSPM electrodes spanning multiple slices. This could be improved with smaller electrodes or preferably smaller slice thickness during the CT scan.

CONCLUSIONS
CT analysis serves as a viable approach to determine body surface (and BSPM electrode), as well as epicardial envelope geometry, simultaneously and non-invasively. The geometrical information determined via this method should provide adequate geometrical information to compute inverse problem solutions in vivo.

ACKNOWLEDGMENTS
This work was funded under NIH Training Grant 5-T32-GM-07535-16 and NIH NHLBI Grant 33343.

REFERENCES
Appendix B - Sample Subject Information Sheet Used for *in vivo* Study

Inverse and Forward Problems in Electrocardiography

<table>
<thead>
<tr>
<th><strong>Subject Information Sheet</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject Name:</td>
</tr>
<tr>
<td>Status/Condition:</td>
</tr>
<tr>
<td>Date of Birth:</td>
</tr>
<tr>
<td>Height:</td>
</tr>
</tbody>
</table>

**CT Scan Data**

| CT Scan Date: | # of slices: |
| Magnification factor: | Slice thickness: |
| Distance Between Slices: | Notes: |

**BSPM Data**

| BSPM Date | Notes |
Vest Position Information

Diagram
FRONT
head

front

right

left

n

st
n

bb

feet

BACK
head

left

right

216  180

224  168

217  161

feet

Notes:
Appendix C - Representative DIPStation Data Parameters of CT Scan Slice for One Subject (ARC-NEMA Format)

NEMA01
TOTAL_VOLUMES=1
$VOLUME=1
TOTAL_SCANS=52
$SLICE=1
PATIENT_NAME="/home/dck3/ctimages/subject#3/hosp"
ROWS=512
COLUMNS=512
ROWVEC=1.000000, 0, 0
COLVEC=0, 1.000000, 0
SLICEVEC=0, 0, 1.000000
SPATIAL_UNITS=mm
BITS_ALLOCATED=16
BITS_STORED=16
HIGH_BIT=15
PIXEL_REPRESENTATION=UNSIGNED
PADDING=16
$SLICE=1
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.001", 4096
$SLICE=2
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.002", 4096
$SLICE=3
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.003", 4096
$SLICE=4
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.004", 4096
$SLICE=5
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.005", 4096
$SLICE=6
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.006", 4096
$SLICE=7
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.007", 4096
$SLICE=8
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.008", 4096
$SLICE=9
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.009", 4096
$SLICE=10
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.010", 4096
$SLICE=11
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.011", 4096
$SLICE=12
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.012", 4096
$SLICE=13
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.013", 4096
$SLICE=14
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.014", 4096
$SLICE=15
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.015", 4096
$SLICE=16
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.016", 4096
$SLICE=17
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.017", 4096
$SLICE=18
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.018", 4096
$SLICE=19
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.019", 4096
$SLICE=20
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.020", 4096
$SLICE=21
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.021", 4096
$SLICE=22
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.022", 4096
$SLICE=23
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.023", 4096
$SLICE=24
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.024", 4096
$SLICE=25
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.025", 4096
$SLICE=26
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.026", 4096
$SLICE=27
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.027", 4096
SSLICE=28
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.028", 4096

SSLICE=29
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.029", 4096

SSLICE=30
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.030", 4096

SSLICE=31
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.031", 4096

SSLICE=32
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.032", 4096

SSLICE=33
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.033", 4096

SSLICE=34
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.034", 4096

SSLICE=35
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.035", 4096

SSLICE=36
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.036", 4096

SSLICE=37
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.037", 4096

SSLICE=38
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.038", 4096

SSLICE=39
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.039", 4096

SSLICE=40
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.040", 4096

SSLICE=41
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.041", 4096

SSLICE=42
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.042", 4096

SSLICE=43
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.043", 4096

SSLICE=44
IMAGE_POSITION=0, 0, 0.000000
DATA="ctbild.hosp.044", 4096

SSLICE=45
## Appendix D - Graphical Representation of 224-electrode BSPM Vest

**BSPM Adult Vest (vest created by Dr. Lee)**
(Note - views taken as the patient has the vest on i.e. looking at the vest from the outside.)

<table>
<thead>
<tr>
<th>Right Axillary Line</th>
<th>Front</th>
<th>Left Axillary Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connector #1</td>
<td>Connector #2</td>
<td>Connector #3</td>
</tr>
<tr>
<td>108</td>
<td>96</td>
<td>84</td>
</tr>
<tr>
<td>144</td>
<td>132</td>
<td>120</td>
</tr>
<tr>
<td>143</td>
<td>131</td>
<td>119</td>
</tr>
<tr>
<td>142</td>
<td>130</td>
<td>118</td>
</tr>
<tr>
<td>141</td>
<td>129</td>
<td>117</td>
</tr>
<tr>
<td>140</td>
<td>128</td>
<td>116</td>
</tr>
<tr>
<td>152</td>
<td>159</td>
<td>151</td>
</tr>
<tr>
<td>160</td>
<td>158</td>
<td>150</td>
</tr>
<tr>
<td>157</td>
<td>149</td>
<td>137</td>
</tr>
<tr>
<td>156</td>
<td>148</td>
<td>136</td>
</tr>
<tr>
<td>155</td>
<td>147</td>
<td>135</td>
</tr>
<tr>
<td>154</td>
<td>146</td>
<td>134</td>
</tr>
<tr>
<td>153</td>
<td>145</td>
<td>133</td>
</tr>
</tbody>
</table>

51
<table>
<thead>
<tr>
<th>Left Axillary Line</th>
<th>Back</th>
<th>Right Axillary Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connector #4</td>
<td></td>
<td>Connector #5</td>
</tr>
<tr>
<td>216   204</td>
<td>192  180</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td></td>
</tr>
<tr>
<td>215   203</td>
<td>191  179</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td></td>
</tr>
<tr>
<td>214   202</td>
<td>190  178</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td></td>
</tr>
<tr>
<td>213   201</td>
<td>189  177</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td></td>
</tr>
<tr>
<td>224   212</td>
<td>200  188  176  168</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td>o    o</td>
</tr>
<tr>
<td>223   211</td>
<td>199  187  175  167</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td>o    o</td>
</tr>
<tr>
<td>222   210</td>
<td>198  186  174  166</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td>o    o</td>
</tr>
<tr>
<td>221   209</td>
<td>197  185  173  165</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td>o    o</td>
</tr>
<tr>
<td>220   208</td>
<td>196  184  172  164</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td>o    o</td>
</tr>
<tr>
<td>219   207</td>
<td>195  183  171  163</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td>o    o</td>
</tr>
<tr>
<td>218   206</td>
<td>194  182  170  162</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td>o    o</td>
</tr>
<tr>
<td>217   205</td>
<td>193  181  169  161</td>
<td></td>
</tr>
<tr>
<td>o      o</td>
<td>o    o</td>
<td>o    o</td>
</tr>
</tbody>
</table>
Appendix E - Program Used to Convert CT Data to 3-D Body Surface and Epicardial Matrices

******************************************************************************
* PROGRAM Conversion 
* *
* This program reads in region of interest and point of interest data output 
* from DIPStation. 
* *
* Inputs 
* a) file name containing inputs which includes the following 
* 1) file name of point of interest for each slice 
* 2) file name of region of interest for each slice 
* 3) file name of neighbor table 
* 3) number of body surface slice files (one file per slice) 
* 4) number of epicardial surface slice files (one file per slice) 
* *
* 5) thickness of each slice 
* 6) distance between slices 
* 7) inslice resolution (mm/pixel) 
* 8) x "origin" coordinate 
* 9) y "origin" coordinate 
* 10) z "origin" coordinate 
* 11) ROI offset for epicardial slices 
* 12) name of output file for 3D coordinates on body surface 
* 13) name of output file for 3D coordinates on epicardium 
* 14) number of points to skip on epicardium to "skip" between 
* "real" points 
* *
* Outputs 
* a) file of 3D coordinates on the body surface 
* b) file of 3D coordinates on the epicardium 
* *
* This program was written by David Kaelber starting on 24 November 1993. 
******************************************************************************

PROGRAM CONVERSION

IMPLICIT NONE ! force all variable to be ! declared

INTEGER BSNSLICE ! number of body surface slices
INTEGER ESNSLICE ! number of epicardial surface slices
INTEGER COLUMN ! column index for ES mesh
INTEGER ROW ! row index for ES mesh
INTEGER COUNTER ! dummy lop variable
INTEGER POINT ! points of interest
INTEGER ESPPOINTS ! number of points to output for
REAL*16 SLICE ! particular slice
REAL*16 DISTANCE ! distance between slices in mm
REAL*16 ELECTRODE ! electrode numbers in BSPM vest
REAL*16 BSCOOR(0:512,1:3) ! 3D position coordinate
! matrix of body
! surface
REAL*16 ESCOOR(0:4096,1:3) ! 3D position coordinate
! matrix of epicardial
REAL*16 NEIGH(1:512,1:4) ! array for neighbor table
REAL*16 RESOLUTION ! inplane resolution
REAL*16 ROIOFFSET ! starting slice number for
! epicardial surface
! slices
REAL*16 TEMP1, TEMP2 ! temporary storage variables
REAL*16 THICKNESS ! thickness of each slice in mm
REAL*16 XORIGIN ! x coordinate of origin
REAL*16 YORIGIN ! y coordinate of origin
REAL*16 ZORIGIN ! z coordinate of origin
CHARACTER*50 TEMP ! temporary variable
CHARACTER*16 FILENAME ! file name
CHARACTER*16 INFILE ! file name of input file
! containing input
! parameters
CHARACTER*16 POIFILE ! file name of point of interest
! for each slice
CHARACTER*16 ROIFILE ! file name of region of
! interest for each slice
CHARACTER*16 NEIGHFILE ! file name of neighbor file
CHARACTER*16 BSOUTFILE ! file name of output file
! containing 3D coordinates
! of the body surface
CHARACTER*16 ESOUTFILE ! file name of output file
! containing 3D coordinates
! of the epicardial surface

! get file name with input parameters
WRITE (6, *) 'Enter file name with start-up parameters.'
READ (5, *) INFILE

! open file
CLOSE(20)
OPEN(UNIT=20, FILE=INFILE, FORM='FORMATTED')

! read start-up parameters
READ (20, FMT=('(16(A))')) POIFILE
READ (20, FMT=('(16(A))')) ROIFILE
READ (20, FMT=('(16(A))')) NEIGHFILE
READ (20, FMT=('(13)')) BSNSLICE
READ (20, FMT=('(13)')) ESNSLICE
READ (20, FMT=('(F3.0)')) THICKNESS
READ (20, FMT=('(F3.0)')) DISTANCE
READ (20, FMT=(F3.1)) RESOLUTION
READ (20, FMT=(F3.0)) XORIGIN
READ (20, FMT=(F3.0)) YORIGIN
READ (20, FMT=(F3.0)) ZORIGIN
READ (20, FMT=(F3.0)) ROIOFFSET
READ (20, FMT=(16(A))) BSOUTFILE
READ (20, FMT=(16(A))) ESOUTFILE
READ (20, FMT=(I3)) ESPOINTS
 C PRINT *,YORIGIN,ZORIGIN
! close input parameters file
CLOSE (20)

! open point of interest files
POINT=1.
OPEN(UNIT=21, FILE=BSOUTFILE, FORM='FORMATTED')
DO SLICE=1,BSNSLICE
   IF (SLICE .LE. 9) THEN
      FILENAME=POIFILE(1:(INDEX(POIFILE," ")-1))
      //CHAR(SLICE+48)
   ELSE IF ((SLICE .GT. 9) .AND. (SLICE .LE. 19)) THEN
      FILENAME=POIFILE(1:(INDEX(POIFILE," ")-1))
      //CHAR(49)//CHAR(SLICE-10+48)
   ELSE IF ((SLICE .GT. 19) .AND. (SLICE .LE. 29)) THEN
      FILENAME=POIFILE(1:(INDEX(POIFILE," ")-1))
      //CHAR(50)//CHAR(SLICE-20+48)
   ELSE IF ((SLICE .GT. 29) .AND. (SLICE .LE. 39)) THEN
      FILENAME=POIFILE(1:(INDEX(POIFILE," ")-1))
      //CHAR(51)//CHAR(SLICE-30+48)
   ELSE IF ((SLICE .GT. 39) .AND. (SLICE .LE. 49)) THEN
      FILENAME=POIFILE(1:(INDEX(POIFILE," ")-1))
      //CHAR(52)//CHAR(SLICE-40+48)
   ELSE IF ((SLICE .GT. 49) .AND. (SLICE .LE. 59)) THEN
      FILENAME=POIFILE(1:(INDEX(POIFILE," ")-1))
      //CHAR(53)//CHAR(SLICE-50+48)
   ELSE IF ((SLICE .GT. 59) .AND. (SLICE .LE. 69)) THEN
      FILENAME=POIFILE(1:(INDEX(POIFILE," ")-1))
      //CHAR(54)//CHAR(SLICE-60+48)
   END IF
   OPEN(UNIT=20, FILE=FILENAME, FORM='FORMATTED')
   READ (20, FMT='((A))', END=100) TEMP
10  READ (20, FMT='(F3.0,21X,2(F3.0,5X))', END=100)
   ELECTRODE,TEMP1,TEMP2
   IF ((INT(BSCOOR(ELECTRODE,1))) .NE. 0) THEN
      WRITE (6, FMT='(A,I3)')
      'A value already exists for electrode ',INT(ELECTRODE)
   END IF
   BSCOOR(ELECTRODE,1)=TEMP1
   BSCOOR(ELECTRODE,2)=TEMP2
   BSCOOR(ELECTRODE,3)=ABS(ZORIGIN-(SLICE-1.)*(DISTANCE+THICKNESS))
   IF (ELECTRODE .EQ. 0.) THEN
GOTO100
END IF
WRITE (6, FMT='(3(F7.2,3X))') ELECTRODE, BSCOOR(ELECTRODE,1),
1 BSCOOR(ELECTRODE,2)
POINT=POINT+1.
GOTO10
100 CLOSE (20)
END DO

! check for possible errors using neighbor table values
OPEN(UNIT=21, FILE=NEIGHFILE, FORM='FORMATTED')
DO ELECTRODE=1,POINT
READ(21, FMT=('(4(F3.0,X))', END=500) NEIGH(ELECTRODE,1),
1 NEIGH(ELECTRODE,2), NEIGH(ELECTRODE,3),
1 NEIGH(ELECTRODE,4)
C WRITE (6, FMT=('(4(F7.2,3X))') NEIGH(ELECTRODE,1),
C 1 NEIGH(ELECTRODE,2), NEIGH(ELECTRODE,3),
C 1 NEIGH(ELECTRODE,4)
C IF ((((BSCOOR(ELECTRODE,1)) .LE. (BSCOOR(NEIGH(ELECTRODE,1),1),1)))
1 .AND. (((BSCOOR(ELECTRODE,2))
1 .LE. (BSCOOR(NEIGH(ELECTRODE,1),2)))))
1 .AND. (((INT(NEIGH(ELECTRODE,1))) .NE. 0.)) THEN
WRITE (6, FMT=('(A,I3,A,I3)'))
1 'Electrode ',INT(ELECTRODE),
1 ' is to the left of electrode ',
1 INT(NEIGH(ELECTRODE,1))
END IF
IF ((((BSCOOR(ELECTRODE,3)) .GE. (BSCOOR(NEIGH(ELECTRODE,2),3),3)))
1 .AND. (((INT(NEIGH(ELECTRODE,2))) .NE. 0.)) THEN
WRITE (6, FMT=('(A,I3,A,I3)'))
1 'Electrode ',INT(ELECTRODE),
1 ' is above electrode ',
1 INT(NEIGH(ELECTRODE,2))
END IF
IF ((((BSCOOR(ELECTRODE,1)) .GE. (BSCOOR(NEIGH(ELECTRODE,3),1),1)))
1 .AND. (((BSCOOR(ELECTRODE,2))
1 .GE. (BSCOOR(NEIGH(ELECTRODE,3),2))))
1 .AND. (((INT(NEIGH(ELECTRODE,3))) .NE. 0.)) THEN
WRITE (6, FMT=('(A,I3,A,I3)'))
1 'Electrode ',INT(ELECTRODE),
1 ' is to the right of electrode ',
1 INT(NEIGH(ELECTRODE,3))
END IF
IF (((BSCOOR(ELECTRODE,3)) .LE. (BSCOOR(NEIGH(ELECTRODE,4),3),3)))
1 .AND. (((INT(NEIGH(ELECTRODE,4))) .NE. 0.)) THEN
WRITE (6, FMT=('(A,I3,A,I3)'))
1 'Electrode ',INT(ELECTRODE),
1 ' is below electrode ',
57

INT(NEIGH(ELECTRODE,4))

END IF
END DO

CLOSE (21)

! transpose and convert to "real" measurements for x and y
DO ELECTRODE=1,POINT
  BSCOOR(ELECTRODE,1)=ABS(XORIGIN-
  BSCOOR(ELECTRODE,1)*RESOLUTION)
  BSCOOR(ELECTRODE,2)=ABS(YORIGIN-
  BSCOOR(ELECTRODE,2)*RESOLUTION)
  WRITE (6, FMT='(3(F7.2,3X))') ELECTRODE,BSCOOR(ELECTRODE,1),
  BSCOOR(ELECTRODE,2), BSCOOR(ELECTRODE,3)

END DO

! save point of interest file with electrodes in numerical order
OPEN(UNIT=21, FILE=BSOUTFILE, FORM='FORMATTED')
OPEN(UNIT=22, FILE=BSOUTFILE(1:(INDEX(BSOUTFILE," ")-1))//".zx1",
  FORM='FORMATTED')
OPEN(UNIT=23, FILE=BSOUTFILE(1:(INDEX(BSOUTFILE," ")-1))//".zx2",
  FORM='FORMATTED')

DO ELECTRODE=1,POINT-1
  !check for non-assigned electrode
  IF (((((INT(BSCOOR(ELECTRODE,1))) .EQ. 0)) .OR.
    (((INT(BSCOOR(ELECTRODE,2))) .EQ. 0))) .OR.
    (((INT(BSCOOR(ELECTRODE,3))) .EQ. 0))) THEN
    WRITE (6, FMT='(A,I3,A)') 'Electrode ', INT(ELECTRODE),
    ' has not been assigned a value, please check.'
  END IF
  WRITE (21, FMT='(3(I5,3X))')
  INT(BSCOOR(ELECTRODE,1)),
  INT(BSCOOR(ELECTRODE,2)),
  INT(BSCOOR(ELECTRODE,3))
  IF (ELECTRODE .LT. 161) THEN
    WRITE (22, FMT='(2(I5,3X),A,I3,A)')
    CHAR(34),INT(ELECTRODE),CHAR(34)
  ELSE
    WRITE (23, FMT='(2(I5,3X),A,I3,A)')
    CHAR(34),INT(ELECTRODE),CHAR(34)
  END IF

END DO
CLOSE (21)
CLOSE (22)

! open region of interest files
OPEN(UNIT=21, FILE=ESOUTFILE, FORM='FORMATTED')
DO SLICE=1,ESNSLICE
IF (SLICE .LE. 9) THEN
    FILENAME=ROIFILE(1:(INDEX(ROIFILE," ")-1)) //CHAR(SLICE+48)
ELSE IF ((SLICE .GT. 9) .AND. (SLICE .LE. 19)) THEN
    FILENAME=ROIFILE(1:(INDEX(ROIFILE," ")-1)) //CHAR(49)//CHAR(SLICE-10+48)
ELSE IF ((SLICE .GT. 19) .AND. (SLICE .LE. 29)) THEN
    FILENAME=ROIFILE(1:(INDEX(ROIFILE," ")-1)) //CHAR(51)//CHAR(SLICE-20+48)
ELSE IF ((SLICE .GT. 29) .AND. (SLICE .LE. 39)) THEN
    FILENAME=ROIFILE(1:(INDEX(ROIFILE," ")-1)) //CHAR(52)//CHAR(SLICE-30+48)
ELSE IF ((SLICE .GT. 39) .AND. (SLICE .LE. 49)) THEN
    FILENAME=ROIFILE(1:(INDEX(ROIFILE," ")-1)) //CHAR(53)//CHAR(SLICE-40+48)
ELSE IF ((SLICE .GT. 49) .AND. (SLICE .LE. 59)) THEN
    FILENAME=ROIFILE(1:(INDEX(ROIFILE," ")-1)) //CHAR(54)//CHAR(SLICE-50+48)
ELSE IF ((SLICE .GT. 59) .AND. (SLICE .LE. 69)) THEN
    FILENAME=ROIFILE(1:(INDEX(ROIFILE," ")-1)) //CHAR(55)//CHAR(SLICE-60+48)
END IF
OPEN(UNIT=20, FILE=FILENAME, FORM='FORMATTED')
READ (20, FMT='((A))') TEMP
POINT=1.
20  READ (20, FMT='(2(F3.0,1X))', END=200) ESCOOR(POINT,1),
    ESCOOR(POINT,2)
ESCOOR(POINT,1)=ABS(XORIGIN-ESCOOR(POINT,1)*RESOLUTION)
ESCOOR(POINT,2)=ABS(YORIGIN-ESCOOR(POINT,2)*RESOLUTION)
ESCOOR(POINT,3)=ABS(ZORIGIN-(SLICE-1.+ROIOFFSET)*
    (DISTANCE+THICKNESS))
POINT=POINT+1.
GOTO20
200  CLOSE (20)
! determine appropriate epicardial surface points
ELECTRODE=INT(POINT/ESPOINTS)
DO COUNTER=1,(POINT-ELECTRODE+1),ELECTRODE
    WRITE (21, FMT='(3(I5,3X))')
    INT(ESCOOR(COUNTER,1)),INT(ESCOOR(COUNTER,2)),
    INT(ESCOOR(COUNTER,3))
END DO
END DO
CLOSE (21)

! determine region of interest element mesh
OPEN(UNIT=22, FILE=ESOUTFILE(1:(INDEX(ESOUTFILE," ")-1))//".mesh",
    FORM='FORMATTED')
DO COLUMN=0,ESNSLICE-2
    DO ROW=1,ESPOINTS-1
        WRITE (22, FMT='(4(I3,X))')
        ((COLUMN*ESPOINTS)+ROW),
        ((COLUMN*ESPOINTS)+(ROW+1)),
    END DO
END DO
CLOSE (22)
END DO
WRITE (22, FMT='(4(I3,X))')
  ((COLUMN*ES POINTS)+ROW),
  ((COLUMN*ES POINTS)+1),
  (((COLUMN+1)*ES POINTS)+1),
  (((COLUMN+1)*ES POINTS)+1)
WRITE (22, FMT='(4(I3,X))')
  ((COLUMN*ES POINTS)+ROW),
  (((COLUMN+1)*ES POINTS)+1),
  (((COLUMN+1)*ES POINTS)+1),
  (((COLUMN+1)*ES POINTS)+(ROW))
END DO
CLOSE (22)

END
### Appendix F - Neighbor Table for Electrode Position Verification

| 2 218 217 217 | 29 20 28 28 | 60 48 47 47 | 88 76 75 75 |
| 2 217 1 1 | 30 22 21 21 | 60 47 59 59 | 88 75 87 87 |
| 3 219 218 218 | 30 21 29 29 | 84 72 48 48 | 89 77 76 76 |
| 3 218 2 2 | 31 23 22 22 | 84 48 60 60 | 89 76 88 88 |
| 4 220 219 219 | 31 22 30 30 | 62 50 49 49 | 90 78 77 77 |
| 4 219 3 3 | 38 26 25 25 | 62 49 61 61 | 90 77 89 89 |
| 4 24 220 220 | 38 25 37 37 | 63 51 50 50 | 91 79 78 78 |
| 24 221 220 220 | 39 27 26 26 | 63 50 62 62 | 91 79 78 90 |
| 5 24 4 4 | 39 26 38 38 | 64 52 51 51 | 92 80 79 79 |
| 16 222 221 221 | 40 28 27 27 | 64 51 63 63 | 92 79 91 91 |
| 16 221 24 24 | 40 27 39 39 | 65 53 52 52 | 93 81 80 80 |
| 8 223 222 222 | 41 29 28 28 | 65 52 64 64 | 93 80 92 92 |
| 8 222 16 16 | 41 28 40 40 | 66 54 53 53 | 94 82 81 81 |
| 10 2 1 1 | 42 30 29 29 | 66 53 65 65 | 94 81 93 93 |
| 10 1 9 9 | 42 29 41 41 | 67 55 54 54 | 95 83 82 82 |
| 11 3 2 2 | 43 31 30 30 | 67 54 66 66 | 95 82 94 94 |
| 11 2 10 10 | 43 30 42 42 | 68 56 55 55 | 98 86 85 85 |
| 12 4 3 3 | 44 32 31 31 | 68 55 67 67 | 98 85 97 97 |
| 12 3 11 11 | 44 31 43 43 | 69 57 56 56 | 99 87 86 86 |
| 13 5 4 4 | 45 33 32 32 | 69 56 68 68 | 99 86 98 98 |
| 13 4 12 12 | 45 32 44 44 | 70 58 57 57 | 100 88 87 87 |
| 14 6 5 5 | 46 34 33 33 | 70 57 69 69 | 100 87 99 99 |
| 14 5 13 13 | 46 33 45 45 | 71 59 58 58 | 101 89 88 88 |
| 15 7 6 6 | 47 35 34 34 | 71 58 70 70 | 101 88 100 100 |
| 15 6 14 14 | 47 34 46 46 | 74 62 61 61 | 102 90 89 89 |
| 7 8 16 16 | 48 36 35 35 | 74 61 73 73 | 102 89 101 101 |
| 7 16 6 6 | 48 35 47 47 | 75 63 62 62 | 103 91 90 90 |
| 6 16 24 24 | 72 36 48 48 | 75 62 74 74 | 103 90 102 102 |
| 6 24 5 5 | 50 38 37 37 | 76 64 63 63 | 104 92 91 91 |
| 18 10 9 9 | 50 37 49 49 | 76 63 75 75 | 104 91 103 103 |
| 18 9 17 17 | 51 39 38 38 | 77 65 64 64 | 105 93 92 92 |
| 19 11 10 10 | 51 38 50 50 | 77 64 76 76 | 105 92 104 104 |
| 19 10 18 18 | 52 40 39 39 | 78 66 65 65 | 106 94 93 93 |
| 20 12 11 11 | 52 39 51 51 | 78 65 77 77 | 106 93 105 105 |
| 20 11 19 19 | 53 41 40 40 | 79 67 66 66 | 107 95 94 94 |
| 21 13 12 12 | 53 40 52 52 | 79 66 78 78 | 107 94 106 106 |
| 21 12 20 20 | 54 42 41 41 | 80 68 67 67 | 110 98 97 97 |
| 22 14 13 13 | 54 41 53 53 | 80 67 79 79 | 110 97 109 109 |
| 22 13 21 21 | 55 43 42 42 | 81 69 68 68 | 111 99 98 98 |
| 23 15 14 14 | 55 42 54 54 | 81 68 80 80 | 111 99 98 110 |
| 23 14 22 22 | 56 44 43 43 | 82 70 69 69 | 112 100 99 99 |
| 26 18 17 17 | 56 43 55 55 | 82 69 81 81 | 112 99 111 111 |
| 26 17 25 25 | 57 45 44 44 | 83 71 70 70 | 113 101 100 100 |
| 27 19 18 18 | 57 44 56 56 | 83 70 82 82 | 113 101 112 112 |
| 27 18 26 26 | 58 46 45 45 | 86 74 73 73 | 114 102 101 101 |
| 28 20 19 19 | 58 45 57 57 | 86 73 85 85 | 114 101 113 113 |
| 28 19 27 27 | 59 47 46 46 | 87 75 74 74 | 115 103 102 102 |
| 29 21 20 20 | 59 46 58 58 | 87 74 86 86 | 115 102 114 114 |
## Appendix H - Representative POI Data Slice

<table>
<thead>
<tr>
<th>Point</th>
<th>x(mm)</th>
<th>y(mm)</th>
<th>value()</th>
</tr>
</thead>
<tbody>
<tr>
<td>131hospnew [0] slice 10</td>
<td>140.000</td>
<td>238.000</td>
<td>62222.000</td>
</tr>
<tr>
<td>119hospnew [0] slice 10</td>
<td>172.500</td>
<td>231.000</td>
<td>65294.000</td>
</tr>
<tr>
<td>107hospnew [0] slice 10</td>
<td>202.500</td>
<td>218.000</td>
<td>19210.000</td>
</tr>
<tr>
<td>71 hospnew [0] slice 10</td>
<td>290.000</td>
<td>227.500</td>
<td>49416.000</td>
</tr>
<tr>
<td>59 hospnew [0] slice 10</td>
<td>314.500</td>
<td>222.000</td>
<td>42766.000</td>
</tr>
<tr>
<td>47 hospnew [0] slice 10</td>
<td>349.500</td>
<td>226.000</td>
<td>270.000</td>
</tr>
<tr>
<td>215hospnew [0] slice 10</td>
<td>390.500</td>
<td>388.000</td>
<td>65294.000</td>
</tr>
<tr>
<td>203hospnew [0] slice 10</td>
<td>322.500</td>
<td>404.500</td>
<td>65294.000</td>
</tr>
<tr>
<td>179hospnew [0] slice 10</td>
<td>164.000</td>
<td>407.500</td>
<td>65294.000</td>
</tr>
</tbody>
</table>
### Appendix I - Representative ROI Data Slice

<table>
<thead>
<tr>
<th>ROI object 1:</th>
<th>315</th>
<th>234</th>
<th>346</th>
<th>276</th>
<th>314</th>
<th>321</th>
</tr>
</thead>
<tbody>
<tr>
<td>267 227</td>
<td>316</td>
<td>235</td>
<td>347</td>
<td>277</td>
<td>313</td>
<td>322</td>
</tr>
<tr>
<td>268 227</td>
<td>317</td>
<td>235</td>
<td>347</td>
<td>278</td>
<td>312</td>
<td>322</td>
</tr>
<tr>
<td>269 227</td>
<td>318</td>
<td>235</td>
<td>347</td>
<td>279</td>
<td>311</td>
<td>322</td>
</tr>
<tr>
<td>270 227</td>
<td>319</td>
<td>236</td>
<td>347</td>
<td>280</td>
<td>310</td>
<td>323</td>
</tr>
<tr>
<td>271 227</td>
<td>320</td>
<td>237</td>
<td>346</td>
<td>281</td>
<td>309</td>
<td>324</td>
</tr>
<tr>
<td>272 227</td>
<td>321</td>
<td>237</td>
<td>346</td>
<td>282</td>
<td>308</td>
<td>325</td>
</tr>
<tr>
<td>273 227</td>
<td>322</td>
<td>237</td>
<td>345</td>
<td>283</td>
<td>307</td>
<td>325</td>
</tr>
<tr>
<td>274 227</td>
<td>323</td>
<td>238</td>
<td>345</td>
<td>284</td>
<td>306</td>
<td>326</td>
</tr>
<tr>
<td>275 227</td>
<td>324</td>
<td>239</td>
<td>345</td>
<td>285</td>
<td>305</td>
<td>326</td>
</tr>
<tr>
<td>276 227</td>
<td>325</td>
<td>239</td>
<td>345</td>
<td>286</td>
<td>304</td>
<td>326</td>
</tr>
<tr>
<td>277 227</td>
<td>326</td>
<td>239</td>
<td>345</td>
<td>287</td>
<td>303</td>
<td>327</td>
</tr>
<tr>
<td>278 227</td>
<td>327</td>
<td>240</td>
<td>344</td>
<td>288</td>
<td>302</td>
<td>328</td>
</tr>
<tr>
<td>279 227</td>
<td>328</td>
<td>241</td>
<td>344</td>
<td>289</td>
<td>301</td>
<td>328</td>
</tr>
<tr>
<td>280 227</td>
<td>329</td>
<td>242</td>
<td>344</td>
<td>290</td>
<td>300</td>
<td>329</td>
</tr>
<tr>
<td>281 227</td>
<td>330</td>
<td>242</td>
<td>343</td>
<td>291</td>
<td>299</td>
<td>330</td>
</tr>
<tr>
<td>282 227</td>
<td>330</td>
<td>243</td>
<td>343</td>
<td>292</td>
<td>299</td>
<td>331</td>
</tr>
<tr>
<td>283 227</td>
<td>331</td>
<td>244</td>
<td>342</td>
<td>293</td>
<td>299</td>
<td>332</td>
</tr>
<tr>
<td>284 227</td>
<td>332</td>
<td>245</td>
<td>342</td>
<td>294</td>
<td>299</td>
<td>333</td>
</tr>
<tr>
<td>285 227</td>
<td>333</td>
<td>246</td>
<td>342</td>
<td>295</td>
<td>298</td>
<td>334</td>
</tr>
<tr>
<td>286 228</td>
<td>334</td>
<td>247</td>
<td>341</td>
<td>296</td>
<td>297</td>
<td>335</td>
</tr>
<tr>
<td>287 228</td>
<td>335</td>
<td>248</td>
<td>341</td>
<td>297</td>
<td>297</td>
<td>336</td>
</tr>
<tr>
<td>288 228</td>
<td>336</td>
<td>249</td>
<td>340</td>
<td>298</td>
<td>296</td>
<td>337</td>
</tr>
<tr>
<td>289 228</td>
<td>337</td>
<td>250</td>
<td>339</td>
<td>299</td>
<td>296</td>
<td>338</td>
</tr>
<tr>
<td>290 229</td>
<td>337</td>
<td>251</td>
<td>339</td>
<td>300</td>
<td>295</td>
<td>339</td>
</tr>
<tr>
<td>291 229</td>
<td>338</td>
<td>252</td>
<td>338</td>
<td>301</td>
<td>295</td>
<td>340</td>
</tr>
<tr>
<td>292 229</td>
<td>339</td>
<td>253</td>
<td>337</td>
<td>302</td>
<td>294</td>
<td>341</td>
</tr>
<tr>
<td>293 229</td>
<td>339</td>
<td>254</td>
<td>336</td>
<td>303</td>
<td>293</td>
<td>342</td>
</tr>
<tr>
<td>294 229</td>
<td>340</td>
<td>255</td>
<td>335</td>
<td>304</td>
<td>292</td>
<td>343</td>
</tr>
<tr>
<td>295 229</td>
<td>341</td>
<td>256</td>
<td>334</td>
<td>304</td>
<td>291</td>
<td>343</td>
</tr>
<tr>
<td>296 230</td>
<td>341</td>
<td>257</td>
<td>333</td>
<td>305</td>
<td>290</td>
<td>343</td>
</tr>
<tr>
<td>297 230</td>
<td>342</td>
<td>258</td>
<td>332</td>
<td>306</td>
<td>289</td>
<td>344</td>
</tr>
<tr>
<td>298 230</td>
<td>343</td>
<td>259</td>
<td>331</td>
<td>306</td>
<td>288</td>
<td>345</td>
</tr>
<tr>
<td>299 230</td>
<td>343</td>
<td>260</td>
<td>330</td>
<td>307</td>
<td>287</td>
<td>346</td>
</tr>
<tr>
<td>300 231</td>
<td>343</td>
<td>261</td>
<td>329</td>
<td>308</td>
<td>286</td>
<td>346</td>
</tr>
<tr>
<td>301 231</td>
<td>343</td>
<td>262</td>
<td>328</td>
<td>309</td>
<td>285</td>
<td>346</td>
</tr>
<tr>
<td>302 231</td>
<td>344</td>
<td>263</td>
<td>327</td>
<td>310</td>
<td>284</td>
<td>347</td>
</tr>
<tr>
<td>303 231</td>
<td>344</td>
<td>264</td>
<td>326</td>
<td>311</td>
<td>283</td>
<td>347</td>
</tr>
<tr>
<td>304 231</td>
<td>344</td>
<td>265</td>
<td>325</td>
<td>312</td>
<td>282</td>
<td>348</td>
</tr>
<tr>
<td>305 231</td>
<td>345</td>
<td>266</td>
<td>324</td>
<td>313</td>
<td>281</td>
<td>348</td>
</tr>
<tr>
<td>306 231</td>
<td>345</td>
<td>267</td>
<td>323</td>
<td>314</td>
<td>280</td>
<td>348</td>
</tr>
<tr>
<td>307 231</td>
<td>345</td>
<td>268</td>
<td>322</td>
<td>315</td>
<td>279</td>
<td>348</td>
</tr>
<tr>
<td>308 232</td>
<td>345</td>
<td>269</td>
<td>321</td>
<td>316</td>
<td>278</td>
<td>348</td>
</tr>
<tr>
<td>309 232</td>
<td>345</td>
<td>270</td>
<td>320</td>
<td>317</td>
<td>277</td>
<td>348</td>
</tr>
<tr>
<td>310 233</td>
<td>346</td>
<td>271</td>
<td>319</td>
<td>318</td>
<td>276</td>
<td>347</td>
</tr>
<tr>
<td>311 233</td>
<td>346</td>
<td>272</td>
<td>318</td>
<td>318</td>
<td>275</td>
<td>347</td>
</tr>
<tr>
<td>312 233</td>
<td>346</td>
<td>273</td>
<td>317</td>
<td>319</td>
<td>274</td>
<td>346</td>
</tr>
<tr>
<td>313 233</td>
<td>346</td>
<td>274</td>
<td>316</td>
<td>320</td>
<td>273</td>
<td>345</td>
</tr>
<tr>
<td>314 234</td>
<td>346</td>
<td>275</td>
<td>315</td>
<td>321</td>
<td>273</td>
<td>344</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>272</td>
<td>343</td>
<td>236</td>
<td>324</td>
<td>221</td>
<td>285</td>
<td>230</td>
</tr>
<tr>
<td>272</td>
<td>342</td>
<td>236</td>
<td>323</td>
<td>221</td>
<td>284</td>
<td>231</td>
</tr>
<tr>
<td>271</td>
<td>341</td>
<td>235</td>
<td>322</td>
<td>221</td>
<td>283</td>
<td>232</td>
</tr>
<tr>
<td>270</td>
<td>340</td>
<td>235</td>
<td>321</td>
<td>220</td>
<td>282</td>
<td>233</td>
</tr>
<tr>
<td>269</td>
<td>339</td>
<td>234</td>
<td>320</td>
<td>220</td>
<td>281</td>
<td>234</td>
</tr>
<tr>
<td>269</td>
<td>338</td>
<td>234</td>
<td>319</td>
<td>220</td>
<td>280</td>
<td>235</td>
</tr>
<tr>
<td>268</td>
<td>337</td>
<td>233</td>
<td>318</td>
<td>220</td>
<td>279</td>
<td>236</td>
</tr>
<tr>
<td>268</td>
<td>336</td>
<td>233</td>
<td>317</td>
<td>221</td>
<td>278</td>
<td>237</td>
</tr>
<tr>
<td>267</td>
<td>335</td>
<td>232</td>
<td>316</td>
<td>221</td>
<td>277</td>
<td>238</td>
</tr>
<tr>
<td>266</td>
<td>334</td>
<td>232</td>
<td>315</td>
<td>220</td>
<td>276</td>
<td>239</td>
</tr>
<tr>
<td>265</td>
<td>333</td>
<td>231</td>
<td>314</td>
<td>220</td>
<td>275</td>
<td>240</td>
</tr>
<tr>
<td>264</td>
<td>332</td>
<td>231</td>
<td>313</td>
<td>221</td>
<td>274</td>
<td>241</td>
</tr>
<tr>
<td>263</td>
<td>331</td>
<td>230</td>
<td>312</td>
<td>221</td>
<td>273</td>
<td>242</td>
</tr>
<tr>
<td>262</td>
<td>330</td>
<td>230</td>
<td>311</td>
<td>221</td>
<td>272</td>
<td>243</td>
</tr>
<tr>
<td>261</td>
<td>330</td>
<td>229</td>
<td>310</td>
<td>222</td>
<td>271</td>
<td>244</td>
</tr>
<tr>
<td>260</td>
<td>330</td>
<td>229</td>
<td>309</td>
<td>222</td>
<td>270</td>
<td>245</td>
</tr>
<tr>
<td>259</td>
<td>330</td>
<td>229</td>
<td>308</td>
<td>222</td>
<td>269</td>
<td>246</td>
</tr>
<tr>
<td>258</td>
<td>330</td>
<td>229</td>
<td>307</td>
<td>222</td>
<td>268</td>
<td>247</td>
</tr>
<tr>
<td>257</td>
<td>330</td>
<td>229</td>
<td>306</td>
<td>222</td>
<td>267</td>
<td>248</td>
</tr>
<tr>
<td>256</td>
<td>329</td>
<td>228</td>
<td>305</td>
<td>222</td>
<td>266</td>
<td>249</td>
</tr>
<tr>
<td>255</td>
<td>329</td>
<td>228</td>
<td>304</td>
<td>223</td>
<td>265</td>
<td>250</td>
</tr>
<tr>
<td>254</td>
<td>329</td>
<td>228</td>
<td>303</td>
<td>223</td>
<td>264</td>
<td>251</td>
</tr>
<tr>
<td>253</td>
<td>329</td>
<td>228</td>
<td>302</td>
<td>223</td>
<td>263</td>
<td>252</td>
</tr>
<tr>
<td>252</td>
<td>329</td>
<td>228</td>
<td>301</td>
<td>223</td>
<td>262</td>
<td>253</td>
</tr>
<tr>
<td>251</td>
<td>329</td>
<td>227</td>
<td>300</td>
<td>224</td>
<td>261</td>
<td>254</td>
</tr>
<tr>
<td>250</td>
<td>329</td>
<td>227</td>
<td>299</td>
<td>224</td>
<td>260</td>
<td>255</td>
</tr>
<tr>
<td>249</td>
<td>329</td>
<td>227</td>
<td>298</td>
<td>224</td>
<td>259</td>
<td>256</td>
</tr>
<tr>
<td>248</td>
<td>328</td>
<td>226</td>
<td>297</td>
<td>224</td>
<td>258</td>
<td>257</td>
</tr>
<tr>
<td>247</td>
<td>328</td>
<td>226</td>
<td>296</td>
<td>225</td>
<td>257</td>
<td>258</td>
</tr>
<tr>
<td>246</td>
<td>328</td>
<td>226</td>
<td>295</td>
<td>225</td>
<td>256</td>
<td>259</td>
</tr>
<tr>
<td>245</td>
<td>328</td>
<td>225</td>
<td>294</td>
<td>225</td>
<td>255</td>
<td>260</td>
</tr>
<tr>
<td>244</td>
<td>327</td>
<td>225</td>
<td>293</td>
<td>225</td>
<td>254</td>
<td>261</td>
</tr>
<tr>
<td>243</td>
<td>327</td>
<td>224</td>
<td>292</td>
<td>226</td>
<td>253</td>
<td>262</td>
</tr>
<tr>
<td>242</td>
<td>327</td>
<td>224</td>
<td>291</td>
<td>226</td>
<td>252</td>
<td>263</td>
</tr>
<tr>
<td>241</td>
<td>326</td>
<td>224</td>
<td>290</td>
<td>226</td>
<td>251</td>
<td>264</td>
</tr>
<tr>
<td>240</td>
<td>326</td>
<td>223</td>
<td>289</td>
<td>227</td>
<td>250</td>
<td>265</td>
</tr>
<tr>
<td>239</td>
<td>326</td>
<td>223</td>
<td>288</td>
<td>227</td>
<td>249</td>
<td>266</td>
</tr>
<tr>
<td>238</td>
<td>325</td>
<td>222</td>
<td>287</td>
<td>228</td>
<td>248</td>
<td></td>
</tr>
<tr>
<td>237</td>
<td>325</td>
<td>222</td>
<td>286</td>
<td>229</td>
<td>247</td>
<td></td>
</tr>
</tbody>
</table>
### Appendix J - Sample Body Surface Matrix

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>97</td>
<td>200</td>
<td>148</td>
<td>178</td>
<td>308</td>
<td>140</td>
<td>304</td>
<td>309</td>
<td>140</td>
</tr>
<tr>
<td>92</td>
<td>203</td>
<td>180</td>
<td>177</td>
<td>309</td>
<td>172</td>
<td>301</td>
<td>310</td>
<td>172</td>
</tr>
<tr>
<td>87</td>
<td>205</td>
<td>204</td>
<td>177</td>
<td>309</td>
<td>204</td>
<td>301</td>
<td>312</td>
<td>196</td>
</tr>
<tr>
<td>77</td>
<td>210</td>
<td>236</td>
<td>175</td>
<td>311</td>
<td>228</td>
<td>299</td>
<td>313</td>
<td>228</td>
</tr>
<tr>
<td>81</td>
<td>209</td>
<td>268</td>
<td>178</td>
<td>313</td>
<td>260</td>
<td>305</td>
<td>316</td>
<td>276</td>
</tr>
<tr>
<td>75</td>
<td>215</td>
<td>300</td>
<td>176</td>
<td>309</td>
<td>292</td>
<td>304</td>
<td>310</td>
<td>284</td>
</tr>
<tr>
<td>74</td>
<td>217</td>
<td>324</td>
<td>177</td>
<td>307</td>
<td>324</td>
<td>301</td>
<td>304</td>
<td>324</td>
</tr>
<tr>
<td>68</td>
<td>192</td>
<td>324</td>
<td>181</td>
<td>304</td>
<td>348</td>
<td>299</td>
<td>303</td>
<td>364</td>
</tr>
<tr>
<td>94</td>
<td>234</td>
<td>140</td>
<td>183</td>
<td>295</td>
<td>380</td>
<td>297</td>
<td>305</td>
<td>380</td>
</tr>
<tr>
<td>95</td>
<td>233</td>
<td>180</td>
<td>180</td>
<td>290</td>
<td>404</td>
<td>297</td>
<td>301</td>
<td>412</td>
</tr>
<tr>
<td>91</td>
<td>234</td>
<td>204</td>
<td>186</td>
<td>278</td>
<td>428</td>
<td>298</td>
<td>328</td>
<td>428</td>
</tr>
<tr>
<td>87</td>
<td>241</td>
<td>228</td>
<td>189</td>
<td>266</td>
<td>452</td>
<td>358</td>
<td>247</td>
<td>476</td>
</tr>
<tr>
<td>87</td>
<td>237</td>
<td>260</td>
<td>202</td>
<td>310</td>
<td>140</td>
<td>330</td>
<td>297</td>
<td>140</td>
</tr>
<tr>
<td>85</td>
<td>238</td>
<td>300</td>
<td>203</td>
<td>313</td>
<td>172</td>
<td>326</td>
<td>300</td>
<td>172</td>
</tr>
<tr>
<td>85</td>
<td>242</td>
<td>324</td>
<td>208</td>
<td>314</td>
<td>204</td>
<td>325</td>
<td>302</td>
<td>204</td>
</tr>
<tr>
<td>74</td>
<td>186</td>
<td>300</td>
<td>204</td>
<td>317</td>
<td>228</td>
<td>325</td>
<td>306</td>
<td>236</td>
</tr>
<tr>
<td>104</td>
<td>255</td>
<td>148</td>
<td>209</td>
<td>315</td>
<td>260</td>
<td>327</td>
<td>303</td>
<td>260</td>
</tr>
<tr>
<td>105</td>
<td>260</td>
<td>172</td>
<td>209</td>
<td>311</td>
<td>284</td>
<td>330</td>
<td>297</td>
<td>292</td>
</tr>
<tr>
<td>104</td>
<td>265</td>
<td>212</td>
<td>209</td>
<td>310</td>
<td>316</td>
<td>330</td>
<td>299</td>
<td>324</td>
</tr>
<tr>
<td>101</td>
<td>265</td>
<td>228</td>
<td>210</td>
<td>305</td>
<td>348</td>
<td>330</td>
<td>296</td>
<td>348</td>
</tr>
<tr>
<td>104</td>
<td>268</td>
<td>268</td>
<td>215</td>
<td>296</td>
<td>372</td>
<td>326</td>
<td>292</td>
<td>380</td>
</tr>
<tr>
<td>101</td>
<td>264</td>
<td>300</td>
<td>216</td>
<td>288</td>
<td>404</td>
<td>322</td>
<td>284</td>
<td>404</td>
</tr>
<tr>
<td>102</td>
<td>268</td>
<td>324</td>
<td>210</td>
<td>273</td>
<td>428</td>
<td>328</td>
<td>269</td>
<td>428</td>
</tr>
<tr>
<td>80</td>
<td>185</td>
<td>260</td>
<td>121</td>
<td>262</td>
<td>468</td>
<td>323</td>
<td>258</td>
<td>460</td>
</tr>
<tr>
<td>126</td>
<td>279</td>
<td>140</td>
<td>239</td>
<td>309</td>
<td>140</td>
<td>355</td>
<td>288</td>
<td>140</td>
</tr>
<tr>
<td>122</td>
<td>280</td>
<td>180</td>
<td>238</td>
<td>314</td>
<td>172</td>
<td>356</td>
<td>288</td>
<td>172</td>
</tr>
<tr>
<td>122</td>
<td>282</td>
<td>204</td>
<td>237</td>
<td>313</td>
<td>204</td>
<td>352</td>
<td>288</td>
<td>204</td>
</tr>
<tr>
<td>122</td>
<td>285</td>
<td>228</td>
<td>237</td>
<td>316</td>
<td>228</td>
<td>355</td>
<td>289</td>
<td>228</td>
</tr>
<tr>
<td>127</td>
<td>286</td>
<td>260</td>
<td>241</td>
<td>312</td>
<td>252</td>
<td>351</td>
<td>289</td>
<td>260</td>
</tr>
<tr>
<td>128</td>
<td>281</td>
<td>300</td>
<td>239</td>
<td>314</td>
<td>276</td>
<td>349</td>
<td>287</td>
<td>292</td>
</tr>
<tr>
<td>125</td>
<td>285</td>
<td>324</td>
<td>240</td>
<td>309</td>
<td>316</td>
<td>355</td>
<td>284</td>
<td>324</td>
</tr>
<tr>
<td>118</td>
<td>282</td>
<td>356</td>
<td>246</td>
<td>303</td>
<td>348</td>
<td>355</td>
<td>278</td>
<td>348</td>
</tr>
<tr>
<td>115</td>
<td>280</td>
<td>380</td>
<td>252</td>
<td>296</td>
<td>372</td>
<td>355</td>
<td>273</td>
<td>372</td>
</tr>
<tr>
<td>116</td>
<td>278</td>
<td>412</td>
<td>261</td>
<td>288</td>
<td>404</td>
<td>356</td>
<td>271</td>
<td>404</td>
</tr>
<tr>
<td>117</td>
<td>271</td>
<td>436</td>
<td>266</td>
<td>277</td>
<td>420</td>
<td>360</td>
<td>262</td>
<td>428</td>
</tr>
<tr>
<td>121</td>
<td>262</td>
<td>460</td>
<td>148</td>
<td>253</td>
<td>468</td>
<td>360</td>
<td>257</td>
<td>460</td>
</tr>
<tr>
<td>151</td>
<td>293</td>
<td>140</td>
<td>270</td>
<td>308</td>
<td>140</td>
<td>379</td>
<td>273</td>
<td>140</td>
</tr>
<tr>
<td>147</td>
<td>293</td>
<td>172</td>
<td>269</td>
<td>315</td>
<td>172</td>
<td>375</td>
<td>270</td>
<td>172</td>
</tr>
<tr>
<td>149</td>
<td>296</td>
<td>204</td>
<td>269</td>
<td>315</td>
<td>204</td>
<td>377</td>
<td>266</td>
<td>196</td>
</tr>
<tr>
<td>152</td>
<td>304</td>
<td>228</td>
<td>269</td>
<td>316</td>
<td>236</td>
<td>375</td>
<td>267</td>
<td>228</td>
</tr>
<tr>
<td>155</td>
<td>305</td>
<td>260</td>
<td>268</td>
<td>313</td>
<td>260</td>
<td>373</td>
<td>266</td>
<td>260</td>
</tr>
<tr>
<td>155</td>
<td>297</td>
<td>292</td>
<td>269</td>
<td>309</td>
<td>284</td>
<td>375</td>
<td>262</td>
<td>292</td>
</tr>
<tr>
<td>152</td>
<td>296</td>
<td>324</td>
<td>271</td>
<td>306</td>
<td>316</td>
<td>379</td>
<td>264</td>
<td>324</td>
</tr>
<tr>
<td>151</td>
<td>296</td>
<td>356</td>
<td>267</td>
<td>305</td>
<td>348</td>
<td>378</td>
<td>259</td>
<td>348</td>
</tr>
<tr>
<td>150</td>
<td>288</td>
<td>380</td>
<td>278</td>
<td>303</td>
<td>380</td>
<td>384</td>
<td>254</td>
<td>380</td>
</tr>
<tr>
<td>149</td>
<td>282</td>
<td>404</td>
<td>281</td>
<td>296</td>
<td>404</td>
<td>384</td>
<td>254</td>
<td>412</td>
</tr>
<tr>
<td>151</td>
<td>274</td>
<td>428</td>
<td>279</td>
<td>282</td>
<td>420</td>
<td>385</td>
<td>253</td>
<td>436</td>
</tr>
<tr>
<td>148</td>
<td>264</td>
<td>452</td>
<td>329</td>
<td>250</td>
<td>468</td>
<td>380</td>
<td>254</td>
<td>468</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>176</td>
<td>105</td>
<td>140</td>
<td>174</td>
<td>92</td>
<td>372</td>
<td>118</td>
<td>117</td>
<td>260</td>
</tr>
<tr>
<td>175</td>
<td>98</td>
<td>156</td>
<td>177</td>
<td>93</td>
<td>404</td>
<td>120</td>
<td>116</td>
<td>284</td>
</tr>
<tr>
<td>175</td>
<td>95</td>
<td>188</td>
<td>178</td>
<td>96</td>
<td>428</td>
<td>115</td>
<td>115</td>
<td>316</td>
</tr>
<tr>
<td>174</td>
<td>94</td>
<td>228</td>
<td>179</td>
<td>99</td>
<td>452</td>
<td>114</td>
<td>114</td>
<td>340</td>
</tr>
<tr>
<td>180</td>
<td>92</td>
<td>252</td>
<td>120</td>
<td>133</td>
<td>140</td>
<td>109</td>
<td>114</td>
<td>372</td>
</tr>
<tr>
<td>175</td>
<td>93</td>
<td>284</td>
<td>122</td>
<td>132</td>
<td>164</td>
<td>112</td>
<td>113</td>
<td>404</td>
</tr>
<tr>
<td>171</td>
<td>93</td>
<td>308</td>
<td>121</td>
<td>126</td>
<td>196</td>
<td>110</td>
<td>112</td>
<td>428</td>
</tr>
<tr>
<td>173</td>
<td>92</td>
<td>340</td>
<td>118</td>
<td>120</td>
<td>228</td>
<td>110</td>
<td>112</td>
<td>452</td>
</tr>
</tbody>
</table>
## Appendix K - Sample Epicardial Matrix

<table>
<thead>
<tr>
<th>227</th>
<th>259</th>
<th>380</th>
<th>233</th>
<th>273</th>
<th>364</th>
<th>226</th>
<th>277</th>
<th>348</th>
<th>202</th>
<th>296</th>
<th>332</th>
</tr>
</thead>
<tbody>
<tr>
<td>202</td>
<td>252</td>
<td>380</td>
<td>198</td>
<td>269</td>
<td>364</td>
<td>188</td>
<td>272</td>
<td>348</td>
<td>165</td>
<td>286</td>
<td>332</td>
</tr>
<tr>
<td>187</td>
<td>230</td>
<td>380</td>
<td>164</td>
<td>251</td>
<td>364</td>
<td>150</td>
<td>252</td>
<td>348</td>
<td>137</td>
<td>254</td>
<td>332</td>
</tr>
<tr>
<td>188</td>
<td>205</td>
<td>380</td>
<td>155</td>
<td>216</td>
<td>364</td>
<td>143</td>
<td>215</td>
<td>348</td>
<td>142</td>
<td>217</td>
<td>332</td>
</tr>
<tr>
<td>198</td>
<td>181</td>
<td>380</td>
<td>180</td>
<td>183</td>
<td>364</td>
<td>173</td>
<td>179</td>
<td>348</td>
<td>171</td>
<td>184</td>
<td>332</td>
</tr>
<tr>
<td>223</td>
<td>180</td>
<td>380</td>
<td>209</td>
<td>157</td>
<td>364</td>
<td>211</td>
<td>175</td>
<td>348</td>
<td>207</td>
<td>173</td>
<td>332</td>
</tr>
<tr>
<td>248</td>
<td>188</td>
<td>380</td>
<td>240</td>
<td>170</td>
<td>364</td>
<td>244</td>
<td>166</td>
<td>348</td>
<td>244</td>
<td>183</td>
<td>332</td>
</tr>
<tr>
<td>269</td>
<td>192</td>
<td>380</td>
<td>269</td>
<td>187</td>
<td>364</td>
<td>259</td>
<td>192</td>
<td>348</td>
<td>279</td>
<td>207</td>
<td>332</td>
</tr>
<tr>
<td>264</td>
<td>217</td>
<td>380</td>
<td>279</td>
<td>222</td>
<td>364</td>
<td>286</td>
<td>224</td>
<td>348</td>
<td>274</td>
<td>244</td>
<td>332</td>
</tr>
<tr>
<td>256</td>
<td>242</td>
<td>380</td>
<td>267</td>
<td>257</td>
<td>364</td>
<td>267</td>
<td>259</td>
<td>348</td>
<td>244</td>
<td>278</td>
<td>332</td>
</tr>
<tr>
<td>228</td>
<td>266</td>
<td>372</td>
<td>229</td>
<td>277</td>
<td>356</td>
<td>200</td>
<td>278</td>
<td>340</td>
<td>214</td>
<td>295</td>
<td>324</td>
</tr>
<tr>
<td>200</td>
<td>262</td>
<td>372</td>
<td>191</td>
<td>269</td>
<td>356</td>
<td>164</td>
<td>269</td>
<td>340</td>
<td>177</td>
<td>286</td>
<td>324</td>
</tr>
<tr>
<td>174</td>
<td>245</td>
<td>372</td>
<td>154</td>
<td>246</td>
<td>356</td>
<td>137</td>
<td>238</td>
<td>340</td>
<td>142</td>
<td>261</td>
<td>324</td>
</tr>
<tr>
<td>170</td>
<td>217</td>
<td>372</td>
<td>157</td>
<td>208</td>
<td>356</td>
<td>148</td>
<td>202</td>
<td>340</td>
<td>143</td>
<td>224</td>
<td>324</td>
</tr>
<tr>
<td>183</td>
<td>191</td>
<td>372</td>
<td>188</td>
<td>179</td>
<td>356</td>
<td>184</td>
<td>177</td>
<td>340</td>
<td>173</td>
<td>194</td>
<td>324</td>
</tr>
<tr>
<td>211</td>
<td>186</td>
<td>372</td>
<td>209</td>
<td>163</td>
<td>356</td>
<td>218</td>
<td>169</td>
<td>340</td>
<td>210</td>
<td>184</td>
<td>324</td>
</tr>
<tr>
<td>239</td>
<td>190</td>
<td>372</td>
<td>247</td>
<td>167</td>
<td>356</td>
<td>249</td>
<td>180</td>
<td>340</td>
<td>247</td>
<td>187</td>
<td>324</td>
</tr>
<tr>
<td>267</td>
<td>198</td>
<td>372</td>
<td>267</td>
<td>188</td>
<td>356</td>
<td>280</td>
<td>210</td>
<td>340</td>
<td>278</td>
<td>203</td>
<td>324</td>
</tr>
<tr>
<td>273</td>
<td>226</td>
<td>372</td>
<td>284</td>
<td>223</td>
<td>356</td>
<td>277</td>
<td>246</td>
<td>340</td>
<td>276</td>
<td>240</td>
<td>324</td>
</tr>
<tr>
<td>259</td>
<td>252</td>
<td>372</td>
<td>269</td>
<td>261</td>
<td>356</td>
<td>242</td>
<td>274</td>
<td>340</td>
<td>252</td>
<td>277</td>
<td>324</td>
</tr>
</tbody>
</table>