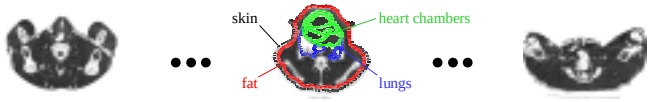
A 3D Computational Torso Model for Electrocardiology

Martyn Nash, Judith Thornton and David Paterson (Physiology, Oxford)

Chris Bradley, Leo Cheng and Andrew Pullan (Bioengineering, Auckland)

Supported by the British Heart Foundation and the Wellcome Trust

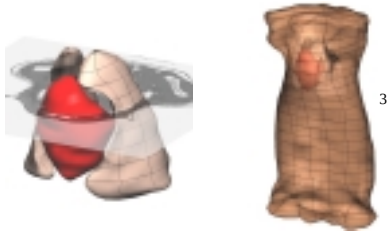
Imaging Porcine Torso Anatomy with CT



Computed tomography was used to image 99 serial cross-sectional slices spanning from neck to abdomen of the porcine torso (1 mm thick, 5 mm spacing). Boundaries between the various organs and tissue layers were identified for surface digitisation as shown for slice 20.

NON-INVASIVE

Development of the Computational Torso Model



For each anatomical surface (endocardium, epicardium, lungs, fat and torso), 3D data sets were created by combining the appropriate digitised data coordinates across all CT slices. A non-linear optimisation procedure, which incorporated non-linear constraints and smoothing, was used to obtain a parametric representation of each surface in 3D space. C^1 cubic Hermite elements were used to define the smoothly continuous anatomical geometry. Full details of the fitting procedure may be found in Bradley *et al.*, *Annals of Biomed Eng*, **25**:96-111, 1997. Approximately 2-10 hours of CPU time were required to fit each surface and the finite element nature of the computations permitted parts of this procedure to be parallelised in a coarse-grained manner. Fitted surfaces for the lungs, epicardium and outer torso (skin) surface are shown above. The table details the numbers of finite element nodes and elements used to define the various surfaces.

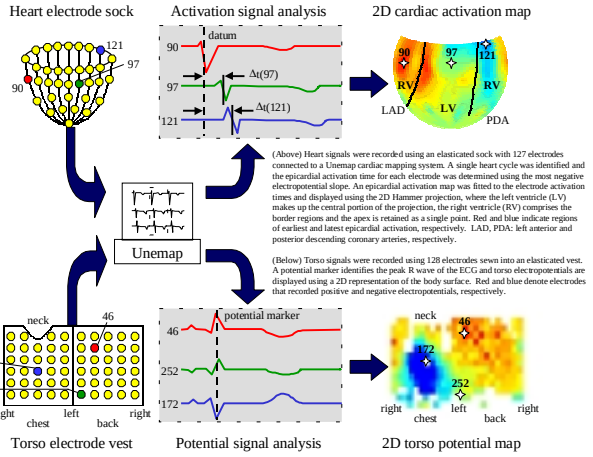
Region	Nodes	Elements
Epicardium	102	112
LV Endocardium	27	30
RV Endocardium	38	42
Left Lung	74	80
Right Lung	74	80
Outer Torso	439	464
TOTAL	754	808

Abstract

Disturbance of heart rhythm is thought to account for around one third of all deaths in the Western World. The electrocardiogram (ECG) is the basic tool used by cardiologists for the non-invasive assessment of cardiac electrical activity. However, because of the limited number of recording sites (usually 12) and its primitive theoretical basis, the ECG has seen little development and remains somewhat subjective. With the advent of new powerful computational techniques, it is now theoretically possible to reconstruct the detailed electrical activity at the outer surface of the heart using a dense array of body surface recordings ('the inverse problem of electrocardiography'). At this stage, the accuracy of these computer generated cardiac maps is unknown in-vivo.

We have recently acquired a series of cross-sectional CT images and developed an anatomically accurate computational model of the porcine torso and its constituents using a non-linear optimisation procedure on OSCAR. We have also recorded simultaneous in-vivo electropotential signals from 128 torso electrodes and from 127 electrodes on the outer surface of the heart. Electrical events have been interpreted and visualised using our porcine model (torso signals) and using an existing 3D anatomico-computational model of the ventricles (heart signals). We propose to use these data to validate the use of new electrical imaging techniques developed by the Oxford-Auckland groups in Physiology and Bioengineering. If the combination of computational modelling and body surface potential mapping can be shown to accurately reproduce cardiac electrical activity, this would be of considerable medical interest as a non-invasive and objective mass screening diagnostic tool.

Cardiac and Body Surface Potential Mapping

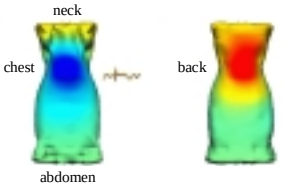


(Above) Heart signals were recorded using an elasticated sock with 127 electrodes connected to a Unemap cardiac mapping system. A single heart cycle was identified and the epicardial activation time for each electrode was determined using the most negative electropotential slope. An epicardial activation map was fitted to the electrode activation times and displayed using the 2D Hammer projection, where the left ventricle (LV) makes up the central portion of the projection, the right ventricle (RV) comprises the border regions and the apex is retained as a single point. Red and blue indicate regions of earliest and latest epicardial activation, respectively. LAD, PDA: left anterior and posterior descending coronary arteries, respectively.

(Below) Torso signals were recorded using 128 electrodes sewn into an elasticated vest. A potential marker identifies the peak R wave of the ECG and torso electropotentials are displayed using a 2D representation of the body surface. Red and blue denote electrodes that recorded positive and negative electropotentials, respectively.

NON-INVASIVE

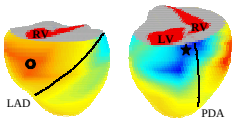
3D Anatomical Electropotential Maps



The dense array of body surface ECG recordings were visualised during peak QRS by fitting a scalar electropotential field onto the outer surface of the computational torso model. A number of anatomical landmarks were located using a FARO mechanical digitiser and incorporated into a non-linear procedure to customise the generic porcine mesh to the experimental porcine model. Anatomical locations of the torso electrodes were also digitised and the 3D positions were orthogonally projected onto the experimental mesh. The recorded ECG signals were then used to fit a continuous field, for which blue and red depict regions of negative and positive electropotential, respectively. For a full animation of the time-varying electropotential field refer to http://www.physiol.ox.ac.uk/~dpj/ and follow the link to our Electrocardiac Mapping web site.

INVASIVE

Objective: 3D Cardiac Electrical Activity



The epicardial activation map recorded *in-vivo* (invasively) during one experiment has been superimposed onto an anatomically accurate model of the cardiac ventricles (LV/RV: left/right ventricle; LAD/PDA: left anterior/posterior descending coronary artery). Red (*) and blue (o) highlight regions of earliest and latest epicardial activation, respectively. For details of this work refer to Nash *et al.*, *J Physiol*, **513.P**:162P, 1998, Nash *et al.*, *J Physiol*, **507.P**:60P, 1998 and Nash *et al.*, *J Appl Physiol*, (accepted for publication) 2000. The main goal of this work is the ability to non-invasively and objectively image the electrical state of the heart. With the advent of new powerful mathematical techniques together with recent advances in high performance computing power, it is now possible to produce epicardial activation or potential maps from densely sampled ECG recordings. What is unknown at this stage is the accuracy of these computational techniques *in-vivo*. Simultaneous electropotential recordings from the torso and epicardial surface, together with detailed measurements of anatomical geometry and electrode locations will be used to quantitatively validate the performance of the new electrocardiac imaging techniques.

?

The Inverse Problem of Electrocardiography

Determining the electrical state of the heart from remote measurements of the electropotential field at the body surface is of considerable medical interest. The inverse problem of electrocardiography is a general name that encapsulates all methods that attempt to compute the time-varying (t) transmembrane potential field, $\phi_m(x,t)$, on the outer surface of the heart (denoted x) from extracellular potential measurements, $\phi(y,t)$, at remote locations on the body surface (denoted y).

In a macroscopic sense, the relationship between the electropotential field and its intracardiac current sources is well understood, via the bidomain field equation:

$$-\nabla\cdot[(G_i(x) + G_e(x))\,\nabla\phi(x,t)] = \nabla\cdot[G_i(x)\,\nabla\phi_m(x,t)]$$

where $G_i(x)$ and $G_e(x)$ are the intra- and extracellular conductivity tensors, respectively. Two meaningful approaches for solving the inverse problem will be quantitatively validated

Epicardial Potential Imaging

The electric field in the source-free region between heart and body surfaces is determined by Laplace's equation, with boundary conditions given by the vanishing of the normal component of current density on the body surface and the unknown epicardial potentials. The result is a linear relationship between the body surface and epicardial potentials. The full approach is given in Greensite *et al.*, *IEEE Trans Biomed Eng*, **45**:1-7, 1998.

Myocardial Surface Activation Imaging

This approach first produces a series of signals at every myocardial surface point in the mesh, which are used to identify epicardial breakthrough sites. The next stage is a computationally intensive optimisation procedure to determine the full myocardial surface activation sequence. The full approach is given in Huiskamp *et al.*, *IEEE Trans Biomed Eng*, **44**:433-446, 1997.

These algorithms have been implemented into a general bioengineering code called CMISS (http://www.esc.auckland.ac.nz/Groups/Bioengineering/CMISS/) using finite element and boundary element techniques, which have been parallelised in a coarse-grained manner. It remains to verify their accuracy and performace using *in-vivo* data.