

A Virtual Reality Toolkit for the Diagnosis and Monitoring of Myocardial Infarctions

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Abstract

We have developed a software system that takes standard electrocardiogram (ECG) input and interprets this input along with user-defined and automatically defined markers to diagnose myocardial infarctions (MI). These pathologies are then automatically represented within a volumetric model of the heart. Over a period of six months 30 patients were monitored using a digital ECG system and this information was used to test and develop our system. It was found that the STEMI (ST segment Elevation MI) were successfully diagnosed, however NSTEMIs (Non-STEMI), although correctly interpreted, were more ambiguous due to the fact that T wave inversions are sometimes seen on normal ECGs. Control ECGs of normal hearts were also taken. The system correctly interpreted this data as being normal. A standard voxel-count metric was developed so that future work in MI monitoring will be possible. The toolkit was found to be beneficial for three possible uses, as a diagnostic tool for clinicians, as a teaching tool for students and also as an information tool for the patient.

Keywords: myocardial infarction, volume graphics, ST elevation, ECG

1. Introduction

Myocardial infarction (MI) is the medical term for “heart attack” and is one of the leading causes of death in the world. ECG (electrocardiography) is used in the diagnosis of MI and the clinician has a time-consuming job in the interpretation of electrocardiographic data. Although the inverse ECG problem is a popular research area, there are very few tools available to cardiology clinicians that give visual 3D representations of cardiac abnormalities [FSD03]. Rich representation of physiological phenomena through graphics is becoming increasingly easier and also more realistic because of rapid technological advances along with ongoing research. We have developed a software system that utilizes these graphical techniques to display MI information derived from ECG input. Real-time volumetric interaction is one of the key features of our system. A hybrid of polygonal mesh graphics and slice-based volumization is the basis of our heart model.

Our ECG system reads in the relatively new SCP (Standard Communications Protocol) file format and uses existing ECG waveform analysis algorithms as well as our own techniques. This paper builds upon the various generations of a system that has been undergoing development over the past three years [ROB] [ROBM04] [MORB03]. The software incorporates an animation system that displays the electrical propagation throughout the heart muscle in synchrony with an inputted ECG file. This choreography between the model and the ECG is done by assigning steps that are defined either manually or automatically. The myocardial infarction interpretation system was built into the existing software which mainly uses user-defined ECG markers. In the evaluation, and to some extent the development, of this stage we needed real ECGs from patients with MIs. Over a six month period we performed ECGs on patients in one of the main national Cardiology centers. This allowed us to monitor the progress and get other data relevant to the study.

In Section 2 we give a brief background to our research. This includes information about the basic

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anatomical/physiological principles, graphical techniques and interpretation techniques relevant to our research. Section 3 describes our data collection methods and the methods for acquisition of ECG data. In section 4 there is an overview of the current and previous software systems within the project. The results are presented and discussed in Section 5 and finally we conclude with a discussion of future possibilities.

2. Background

2.1. Anatomical and Physiological Principles

The heart is an organ mainly consisting of muscle that pumps blood around the body. It is situated in a chest cavity called the mediastinum. The heart itself is supplied by blood vessels called the coronary arteries. Figure 1 demonstrates the main components within the heart.

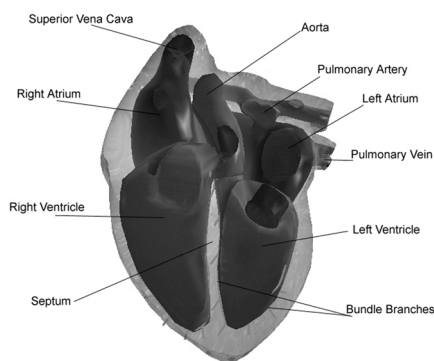


Figure 1: Diagram of the heart.

The heart muscle is triggered by a complex nervous system which produces a strong electrical pulse. This pulse can be monitored from the outside by attaching sensors/leads to various parts of the body. This form of monitoring is called Electrocardiography (ECG). The 12 lead configuration is the standard in clinical practice, and consists of 3 standard leads (I, II and III), 6 precordial leads (V1-V6) and 3 augmented leads (aVR, aVL and aVF). ECG was invented in 1902 by a Dutch physician and physicist called Williem Einthoven. In many areas it is called EKG due to its Dutch heritage. Figure 2 shows a sample ECG from lead II with wave markers. These wave classifications are used in the diagnosis of abnormalities and are normally measured by a physician alongside gridded paper. In our software this is achieved using the actual electrical values.

Myocardial infarction means the death of cells

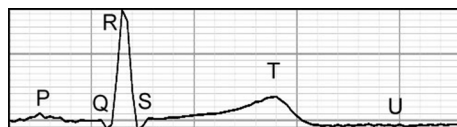


Figure 2: Sample ECG.

within the myocardium i.e., the heart muscle. Clinically, myocardial infarction is considered more of a process than a final condition. There are three steps in this process: Firstly, an occlusion or blockage is caused within a blood vessel supplying the heart. This causes ischemia, which is basically a lack of oxygen to the tissue normally supplied by this blood vessel. Through time, this ischemia turns to injury of the tissue and finally, the last step is infarction where the cells actually die. Figure 3 shows this process. An infarction like this is called an antero-lateral infarction and is caused by an occlusion (e.g. bloodclot) to the left circumflex coronary artery, marginal branch of the left circumflex artery or the diagonal branch of the left anterior descending artery.

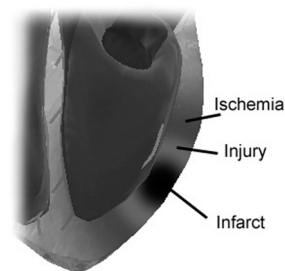


Figure 3: MI Process.

2.2. Graphics and ECG

With the advent of virtual reality and modern graphical techniques, simulations of physiological phenomena have become increasingly realistic. As computer specifications improve, so too does the accuracy and realism of these simulations. There are many advantages with using virtual reality as a method for medical and surgical training. The student/physician gains a greater sense of spatial awareness as well as not compromising patient safety [DPO*03]. Interactivity, volumetric representation and 3D animation are obviously more beneficial in the learning process compared with 2D images or text. Incorporating all of these features brings some problems for the developer if real-time rendering is required. However, volume representation techniques such as slice-based rendering are making

the developer’s job much easier [KSH03]. Cardiac simulation is an area rich in research, however, there is still a lot of scope for new research and development. In accurate simulation projects the model data is often vast due to the large amount of cellular information (fibre orientation, ionic information). Also, simulations often require long processing periods or supercomputers [KNWH03]. We are interested in the inverse ECG problem i.e., deriving model information from ECG input, and one of our main interests is to have a system that runs on a commodity PC in real-time rather than a large-scale supercomputer. CES-Lab is a project that has similar aims regarding system specifications [rC], but is concerned with the opposite problem i.e., the forward ECG problem, deriving ECG information from a cellular model. The modeling of electrical propagation throughout the heart is a common research area [SFE*03]. The inverse ECG problem is considered ill-posed because there are several associated problems. The main problem is that, unless the actual shape, size and location of the heart is known, it is almost impossible to truly represent the inputted ECG. Therefore, assumptions or shortcuts have to be made. Some forward ECG researchers have experimented with introducing abnormalities such as myocardial infarctions to produce ECG information then testing inverse ECG methods by reversing the process [FSD03].

Automatic ECG interpretation and pattern recognition is of key importance to this project and has been an actively researched area for the last 50 years [TS90]. In general, the ultimate aim of this research area is to speed up the process of ECG diagnosis and also to make diagnoses more accurate. Theoretical concepts, however, are more complicated in real-life. A typical example of this is interference due to muscle noise. The processes of pattern recognition and parameter measurement produce information that can be then used in the detection of any abnormalities. Pattern recognition of the ECG waveforms is a problematic area. The most important waveform within the ECG is that of the QRS complex. This is the most predominant element of the ECG and is used for the measurement of heart-rate. The QRS complex is also used as the starting point for many wave detection algorithms. There are many QRS detection algorithms, but most are designed for different purposes, therefore it is difficult to select an “ideal” algorithm [KHO02]. We found that the most viable option for our project was the So and Chan algorithm [SC97]. This algorithm was designed for ambulatory ECG monitors, therefore suiting the real-time specifications of our project. There were many algorithm options from the fields of artificial neural networks [XHT92], genetic algorithms [PCV95], wavelet transforms [KMBB99] and

Table 1: MI Changes

Location of the Infarct Site	Corresponding Leads
Anterior	V3 and V4
Antero-lateral	V5,V6,I and AVL
Septal	V1 and V2
Inferior	II,III and AVF

syntactic pattern recognition [TS90]. While some algorithms used several methods, for example Tataru and Cinar designed a method of interpreting ECG data by integrating statistical and artificial intelligence tools [TC02].

When a patient suffers a myocardial infarction, their ECG changes along with the physiological changes within the heart. In the first few minutes of myocardial infarction (known as the hyper-acute phase) the first indicative change is a tall and more symmetrical T wave. Then, as time progresses, the ST segment becomes elevated. Subsequently there may be other noticeable changes including T wave inversion and also what is known as a pathologic Q wave. Although all these changes are indicative of MI, they may also be present in other pathologies and sometimes even normal hearts. ST segment elevation, however, is considered reasonably indicative of MI and therefore is the strongest ECG evidence for the early recognition of MI [Pha96]. Within the standard 12 lead configuration, each lead corresponds to a certain area of the heart. When a lead displays indicative changes of MI, this normally means that the area corresponding to that specific lead is infarcted. The amount of ST change is also considered proportional to the extent of infarction in that area. Table 1 displays the types of infarctions associated with specific leads. Leads I, II and III are bipolar limb leads, while aVR, aVL and aVF are unipolar limb leads and V1-V6 are unipolar chest leads.

3. Data Collection

Over a six month period we have performed ECGs on patients that satisfy our criteria. We performed the ECGs on-site with our own equipment to ensure that human error was minimized. To date we have performed ECGs on more than 30 patients presenting with signs and symptoms of MI. We have been selective about what kind of MI patient we choose. Patients with strong ST and T wave abnormalities

have been chosen. We have worked alongside cardiology consultants to attain a good knowledge of the area and to receive training in performing ECGs. The hospital that we work with currently uses paper-tracings rather than digital ECG. For this reason, we had to use our own digital ECG equipment. We use a Cardioline Delta 3 12-lead ECG console linked to a laptop via serial-cable. The provided software records the ECG and then allows the user to export it as an SCP (Standard Communication Protocol) file. The SCP file format is a relatively new file format and is aimed at unifying several ECG manufacturers so that inter-operability is possible. Huffman encoding is used to minimise the file-size. Within our database we recorded the following patient information, age, sex, diagnosis, general history, history of MI, history of CABG (Coronary Artery Bypass Graft), smoking status, high blood-pressure, diabetes, high cholesterol, time of onset, time of presentation, time of ECG. Along with these we tracked the patient's blood analyses from time A to time B. These levels included WCC (White Cell Count), HB (Hemoglobin) and troponin levels.

4. System Overview

In the first year of this project we developed a volumetric model of the heart. We acquired a polygonal heart model from the New York School of Medicine, which was designed by consultant cardiologists and graphics designers. The sino-atrial and atrio-ventricular nodes were added to the model and were represented with spheres. The bundle-branches were also added. This model was then volumized using a technique involving an octree-based ray-crossings algorithm [MORB03]. This was later found to be very processor-intensive and unsuitable for our real-time interactivity goals. This was mainly because it used points to represent cells, which requires a lot of processing. We then devised a method of representing the myocardium with a slice-based volume [ROBM04]. Slices were attained by using a very thin viewing field and outputting the resulting image to a file. The color information was then extracted from these files. Figure 4 shows this process, where the white represents myocardial cells and the black is ignored.

These slices were reconstructed along the same axis to produce a volumetric effect. The slices were then classified into different cell-types using different colors. This was done using a commercial editor. In the previous versions of the software there was an artefact produced when the camera was directly parallel to the slices. This has now been rectified by creating a lattice of slices with slices on two planes. The final volume lattice has a resolution of 256X256X100.

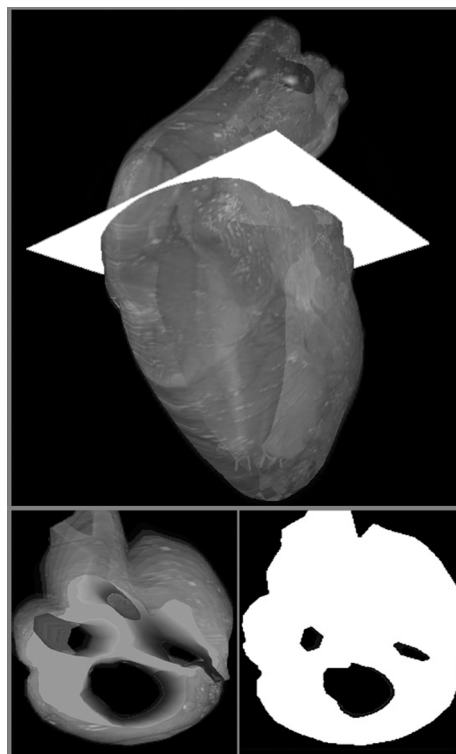


Figure 4: Slice-based texture volumization technique.

This type of texture-based volumization is becoming increasingly popular due to the speed of rendering compared to other forms of volume representation [WEE03] [KSH03]. The voxel datastructure has two main components, the pixel information and the cellular information. The pixel component holds color information and cell-type information and the cellular component holds information regarding specific cell information and animation information such as frame indices and timings.

Our software uses a GUI library called FLTK [rF]. This has OpenGL [rO] capabilities allowing us to display the model information and the ECG information at the same time. The ECG reader can read our own format or SCP format. If the ECG information is encoded we use the default SCP Huffman table as described in the SCP specifications [Eur00]. Figure 5 demonstrates lead II of a sample ECG within the SCP window.

In one of our earlier papers we describe the animation system used in our software [ROB]. This animation system has been changed in various ways. Firstly, the 3D cross-shaped propagation has been changed to a spherical shape. Also, now if there are infarcted cells they are considered by the system as being non-



Figure 5: SCP ECG Window.

conductive. The animation of the electrical propagation is automatically choreographed with markers that are selected by the user or automatically selected using the automatic wave classifier. This wave classifier uses the So and Chan QRS detection algorithm [SC97]. There were other examples of suitable QRS detection algorithm, such as that of Pan and Tompkins [PT85], however Tan et al found, this to be inferior to So and Chan's algorithm [TCC00]. Once the QRS complex is found the other waveforms are found by traversing backwards and forwards from that point. This is not always accurate, so a manual wave classification tool is incorporated into the software.

Myocardial infarctions are now represented within our system as areas around central voxels that correspond to the lead vectors. We introduced voxels within our model by aligning them to axes representing the lead vectors. Figure 6 shows the axes from the center of the heart. The voxels are inputted into the volume where the axes intersect with the model. The electrical propagation animation recognizes the infarcted cells and cannot pass these cells, thus traveling around them. The MI detection system measures the para-

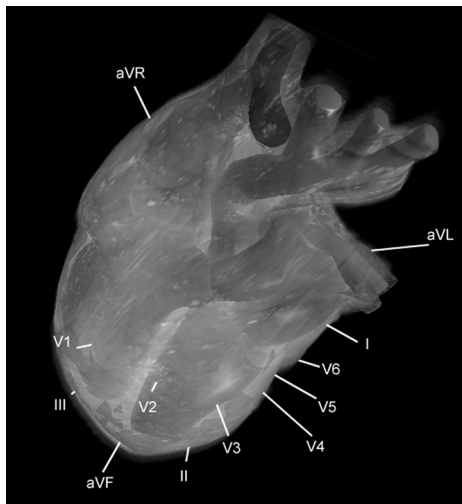


Figure 6: Vector Axes.

meters as found by either the automatic or manual markers system. Currently the system measures the difference between the ST segment and the iso-electric

line for each lead, thus giving an extent, if any, of infarction. These measurements are then used as references for the radius around that specific lead's model-representation voxel. The T waves are also checked for inversion.

We experimented with a method of displaying the electric potential on the outer surface of the heart in real-time. A similar approach was used to classify the outer texture of the heart mesh. We used the axes of the lead vectors in relation to the texture. We used a reference texture with obvious landmarks so that pixels could be assigned different leads. Then, during each frame of the ECG progression the electric values on the texture would be altered to directly correspond with the actual values as read from the ECG file. Figure 7 demonstrates the results of this process.

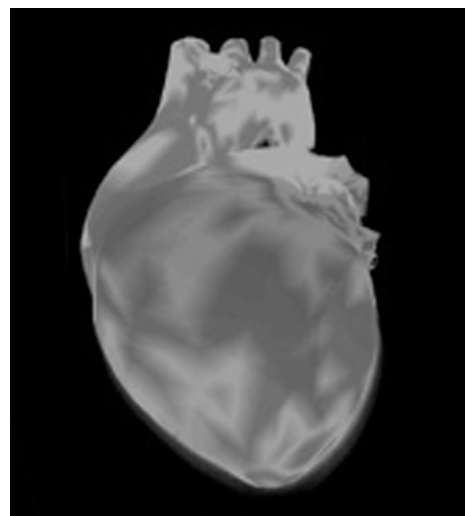


Figure 7: Surface representation on outer mesh.

In order to bring an extra sense of immersion to the software we implemented both stereoscopic viewing features and haptic feedback. We tested our model using a haptic Phantom device but came to the conclusion that it was of no great advantage to the project, as visual feedback was adequate. On the other hand, on implementing stereoscopic viewing conditions, it was found that this would be a very useful feature for a teaching tool version of this software. Rather than using dual-screen goggles we used a system that synchronizes polarized 3D glasses to a CRT monitor [rCRS]. There were several reasons for choosing this method. Firstly, these polarized glasses are relatively inexpensive, and therefore easier to implement in a teaching environment. They also work at driver level, meaning that little programming effort was needed to incorporate them into our software.

It was advised that it would be worthwhile incorporating some kind of standard metric for MI into our system. Currently, cardiologists use chemical measurements from blood analysis to determine the extent and progress of infarction within the myocardium. Although ECG is used to firstly diagnose an infarct, chemical measurements are the standard for monitoring the progress. The purpose of a metric within our system would be to see if these chemical measurements correlate with the measurements within our system. At the moment we use a voxel counter that counts the number of infarcted voxels once the interpretation process is complete. This is of key importance to the next stage of the project which is to compare this voxel count with the blood chemical measurements.

5. Results

Out of 30 patients, approximately 15 had recognizable ST segment elevations. These types of MI are known in clinical practice as STEMI (ST segment elevation MI). However, quite a large proportion of patients that go through the coronary care unit are of the NSTEMI group (Non ST segment elevation MI). These types of MIs are more common because most MIs that start as STEMIs end up this way either through time or treatment. A problem that we noticed was that by the time we would perform an ECG on a specific patient any signs of ST segment elevation may have disappeared. The next stage of the project will involve more onsite presence when a patient arrives at the trauma department. In the interpreter system, we used the common assumption that an ST segment change is only abnormal if it deviates from the iso-electric line more than 1mm on limb leads and 2mm on chest leads. This is a standard that cardiology clinicians use. The software was demonstrated to several cardiology clinicians and it was seen as very beneficial for several reasons. Firstly, as a potential diagnostic tool, it could save the clinician time on measuring the extent of STEMIs. It was also recognised as an invaluable teaching tool giving the student a greater spatial awareness of these kinds of conditions. There is also potential in the area of patient awareness. The software allows a patient to see that an MI is not just readable on graph-paper. Evaluation is of key importance in the next steps of the project. Figures 8, 9 and 10 demonstrate different STEMIs as diagnosed and displayed by our software. T wave abnormalities were also catered for within the interpreter. All T wave abnormalities were interpreted and diagnosed correctly. Most of the NSTEMIs had at least one T wave inversion. However, this is an area that is quite ambiguous and abides by the principle of "rubbish in - rubbish out". The problem is that, although T wave inversions may represent MI in the later stages, this not the only reason for this phenom-

enon and even in some cases this may not even be an abnormality. This T wave inversion system can only be reliable if the clinician knows these limitations and the patient has an already diagnosed MI. This could be of potential importance in the next stage of the project which involves the monitoring of a patient's MI through time. Figure 11 demonstrates an example where the system produced this kind of conflicting information. We took some control ECGs on patients that had no MI or had recovered from MIs and interestingly these ECGs showed the correct results, no pathologies.

As an extra feature, the animation system was altered to incorporate infarction. This is of little interest to the clinician as a diagnostic tool. It is more relevant for a teaching tool to display the electrical propagation around the defined infarcted cells. Figure 12 demonstrates a screen shot of this process.

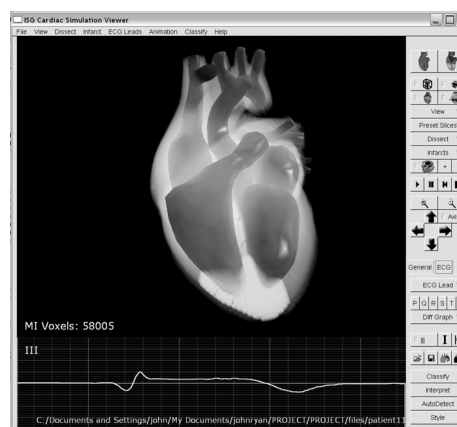


Figure 8: Inferior Infarction.

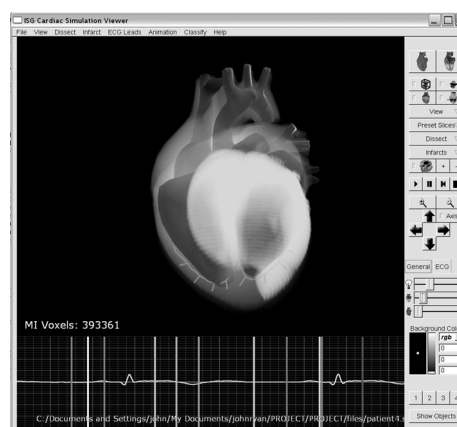


Figure 9: Anterior Infarction.

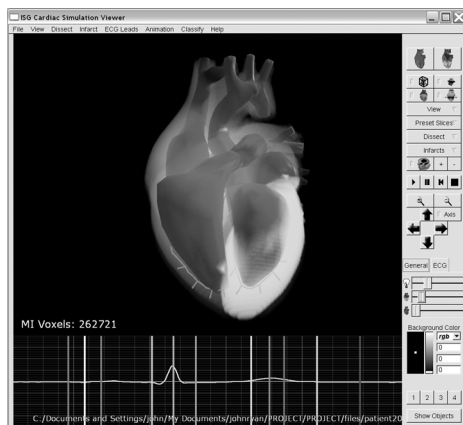


Figure 10: Lateral Infarction.

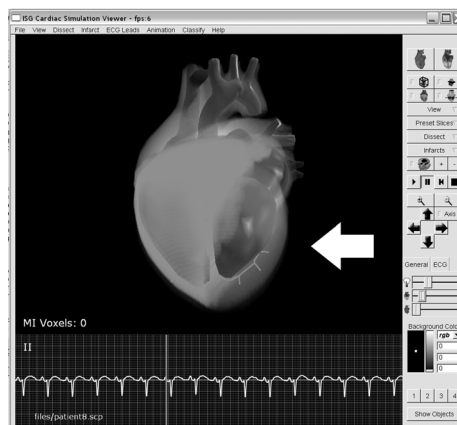


Figure 12: Example of electric propagation (pink) progressing around infarcted area (arrow).

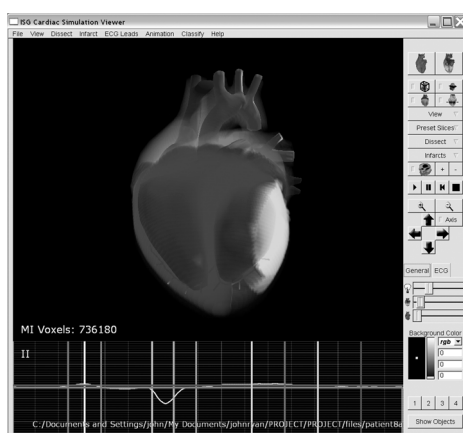


Figure 11: Example of conflict between T wave inversion and ST change, blue represents T wave inversion and green ST change.

6. Conclusions and Future Work

A system that interprets ECG information and user-defined markers to diagnose MIs and represent them automatically within a volumetric model of the heart was successfully developed. We monitored over 30 MI patients that were being treated in the coronary care ward at St James hospital Dublin using a digital ECG monitoring system. These ECGs were then used to test our system. It was found that the STEMIs were successfully diagnosed. However NSTEMIs, although correctly interpreted, were impossible to prove legitimate due to the fact that T wave inversions are sometimes seen on normal ECGs. Control ECGs of normal hearts were also taken. The system correctly interpreted this data as being normal. The toolkit was found to have potential as a diagnostic tool for clinicians, as a teach-

ing tool for students and also as an information tool for the patient.

The next steps in the project involve the monitoring of a patient with a known STEMI to see if the diagnosed size of MI (voxel-count) correlates with chemical measurements within the blood. These chemical measurements are currently the only method that most clinicians use to monitor the progress of an MI. This will allow us to evaluate our system more thoroughly. There are also several improvements that should be made with the current software. For example, the voxel-count does not take into account that the central lead voxels are not at equal distances.

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