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Spatiotemporal Cardiac Activation Sites Localization Using ECG Precordial Leads

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Abstract. A method is proposed for the spatiotemporal localization of the sites of strongest cardiac activity, and for the creation of time varying Pericardium Potential Maps (PPM), with the use of patients' ECG precordial leads. The propossed MATLAB- based software uses the single-moving dipole model, optimized in location and magnitude with respect to the measured leads, and of a realistic Finite Elements (FE) torso model. The PPMs are displayed simultaneously with precordial leads to allow a 3D visual synchronization between the time varying color coded potential map and and the ECG waveforms, which may indicate potential cardiac malignancies. The proposed software was implemented for the analysis of 15 normal patients and 15 patients with cardiac abnormalities. For each case, 20 different sites inside the heart were considered as possible origins of cardiac activity at each instant of time during a complete cardiac cycle. Results show that for normal patients, sources of strongest cardiac activity were located in the atrial region for Q-wave, and the in the ventricle region for both QRS complex and T-wave, whereas for abnormal patients there was no consistency in such locations. The software identified potential cardiac malignancies and their location in 93.33% of the abnormal patients ECGs.

Keywords: ECG, precordial leads, Pericardium Potential Maps, FE heart model, single-moving dipole model.

1. Introduction

Every year more than 5 million patients are diagnosed with some kind of heart disease in the United States [Thom et al., 2006]. While most of the cardiology procedures presently available can be used to obtain an accurate diagnosis of a patient's heart condition, they are mostly invasive, time consuming, expensive or cause discomfort to the patient [Grigyer et al., 2011]. Non-invasive methods have proved to be as effective as invasive methods, without the disadvantages mentioned [He et al., 2003]. The purpose of the research study being reported is to propose an alternative non-invasive, MATLAB-based method to assist the clinician in a preliminary cardiac health diagnosis, using only the patient's ECG signals and a realistic FE torso model. The proposed software program provides a graphical visualization of the localization, in both space and time of the sites of major cardiac activity (Cardiac Activation Sites). Compared to previous ECG- based diagnosis methods, which statistically locate sites of strongest cardiac activity within the heart only, the proposed work has the advantage of providing also a visualization of the electrical potentials on the pericardium over the specific patient's cardiac cycle. As it is well known, inherent limitations of inverse solutions restrict the robustness of approximate solutions, and preliminary diagnostics derived from them would still need verification from other more direct diagnostic methodologies, such as auscultation, x-ray, coronary angiography, clinical chemistry, and others.

The approach taken in arriving at the proposed method consisted of implementing the concept of a single moving dipole model of the human heart, representing its electrical cardiac activity, into the routinely recorded precordial ECG leads [Gulrajani, 1998]. Using a-priori, FEM information, the single moving dipole can be located at each instant of time within a region limited by the heart boundary. a total of 20 possible dipoles sources were evenly spread inside the heart model, including atrial and ventricular regions, as well, as within other conducting fibers. Such inverse solutions take into account inner body properties, such as conductivity of inner organs, blood, bones, etc. [Plonsey and Barr, 2000]. Basically, it gives an approximate solution to the inverse problem of electrocardiography, by providing the location of an equivalent time- dependent dipole solution, directly related to the specific ECG measurements provided. In order to determine whether a patient's ECG may be classified as normal or abnormal, it is necessary to establish normal range of parameters for reference. This range may be taken as the average spatial localization of the normal patient's major source of electrical

activity at a specific time in the cardiac cycle, e.g. the peak of the QRS complex. This part of the solution may be then complemented with the implementation of three-dimensional Pericardium Potential Maps (PPM), which permit visualization of the electric potentials corresponding to the previously-derived cardiac activity locations on the surface of an FE model of the heart. The software was written and implemented in MATLAB and is capable of displaying potential surfaces over the pericardium throughout the entire cardiac cycle, while simultaneously displaying the corresponding precordial ECG measurements. According to experiments made much earlier to evaluate the validity of the moving dipole [Arthur et al., 1971], the local region near the dipole center representing the cardiac activity, is found to be near the pericardium region throughout the cardiac cycle.

2. Materials and Methods

The proposed research requires the use of a software package capable of calculating the precordial lead vector coefficients for different dipole moment locations, and of sets of digitized patient's ECG waveforms. The application of the method also involves band pass filtering, spectral analysis, wave segmentation and three-dimensional FE modeling.

The written software implements the inverse problem of electrocardiography by calculating an equivalent dipole source at each time sample; twenty possible dipole source locations inside the heart were used. The software then reconstructs the original set of precordial signals for each one of the 20 dipole locations. Using the obtained equivalent dipole moments, the potentials at the pericardium are reconstructed as well at each of the time samples. At each time, the strongest dipole moment and its location may be selected as the source of major cardiac electrical activity. Additionally, the software creates a 3D model of the human heart and projects the reconstructed Pericardium Potential Maps at each of the signal samples.

Patients' digitized ECG data constituted the study population. A total of 30 patients, 15 with no cardiac abnormalities and 15 with cardiac abnormalities [Goldberger et al, 2000], were analyzed by the proposed software.

2.1. Lead Vector Coefficients Calculation

The first step of the proposed algorithm requires the calculation of the Lead Vector Coefficients Matrix that associates the patient's precordial measurements with a dipole source inside the heart. Such lead vector coefficients contain all inner conductivities information linking the dipole source location with the location of the precordial leads. These leads are unipolar; that is, electric surface potentials are measured with respect to a distant electrode, which remains at a constant voltage throughout the entire cardiac cycle [Macfarlane et al., 1995]. For a single precordial measurement, the surface potential can be modeled by the single, instantaneous dipole model represented as:

$$v^1(t) = c_x^1 \cdot m_x^1(t) + c_y^1 \cdot m_y^1(t) + c_z^1 \cdot m_z^1(t) \tag{1}$$

where $v^1(t)$ is the measured surface potential, c_x^1, c_y^1 and c_z^1 are lead vector components, $m_x^1(t)$, $m_y^1(t)$ and $m_z^1(t)$ are the dipole moment components of the source, and t is the time. For six precordial leads, Eq. 1 is modeled in matrix form as:

$$[v]^6 = [c]^6[m]^6 \tag{2}$$

where $[v]^6$ is a column vector containing the precordial leads potentials, $[c]^6$ is a 6-by-3 matrix containing the coefficients for the precordial lead vectors, and $[m]^6$ is 1-by-3 matrix containing the components for an equivalent dipole moment.

Lead vectors are calculated by solving the volume conductor problem using Finite Element models of the human torso and heart. The used FE model is conformed by inner organs such as heart, blood, lungs, bones, muscle, fat and skin, as well as their conductivity values at each node. The model uses tetrahedral volume elements with mixed Neumann and Dirichlet boundary conditions [Gulrajani, 1998]. Linear interpolating polynomials are used in order to obtain a constant potential across element interfaces. The coefficients for the lead vectors are computed with the aid of SCIRun/BioPSE open

source simulation software created at the Scientific Computing and Imaging Institute at the University of Utah, capable of solving volume conductor problems [SCIRun, 2010; BioPSE, 2010].

2.2. Dipole Moment Calculation and Signal Reconstruction

Prior to software analysis, patients' ECG signals must be filtered in order to remove high frequency noise due to external electrical activity, and low frequency noise due to power sources and patients movements. Filtering was found to be very effective, as it improved the calculation of the equivalent dipole moments, which was reflected in the high precision of the reconstructed signals. Wave segmentation was found to be necessary to reduce the numerical noise present in the reconstruction of the precordial leads and the PPMs. It was accomplished by dividing the ECG into cardiac cycles and the cycles into wave segments of equal length. During signal reconstruction, the strongest dipole moment in a segment represented the entire segment. This reduced nearly all of the generated numerical noise. In order to properly identify the cardiac cycle duration and frequency, a spectral analysis of the ECG signal was performed using an FFT algorithm [Proakis and Manolakis, 2007], described by the Discrete Fourier Transform equation

$$F(\omega) = \sum_{1}^{N} x(n) e^{-j\omega n} \tag{3}$$

where $F(\omega)$ is the frequency response of the ECG signal, $x(n)$ is the original ECG signal and N is the total number of time samples. The duration of a cardiac cycle was determined by extracting the frequency with the greatest magnitude from $F(\omega)$, and then calculating the period of the signal.

The equivalent dipole moment is calculated at each time sample by solving Eq. 2 for $[m]^6$. However, since six precordial leads were used and there are three components for each one of the six lead vectors, the matrix $[c]^6$ is non-square. Therefore, Eq. 2 is an overdetermined system of linear equations. Overdetermined systems may be solved using the linear least squares equation

$$m = (c^T c)^{-1} c^T v \tag{4}$$

where m is the dipole moment vector, c is the lead vector coefficients matrix, and v is the precordial potentials vector. Since there are 20 different dipole source locations original ECG signal may be reconstructed with 20 different dipole sources.

2.3. Single-moving Dipole and PPM Projection

Analysis and reconstruction are performed in a time- by- time basis; that is, for each time sample of the original set of precordial ECG signal, 20 possible dipole locations were considered and a single dipole was selected as the source of the generated precordial potentials at that single time sample. The dipole with the greatest magnitude may be selected as the source of major electrical activity within the heart at that particular time. Since, the location of the strongest dipole moment can vary from one time sample to another, the dipole location is expected to move from time to time throughout the cardiac cycle, thus identifying the location of major electrical activity at that specific time. A time- varying plot of the cardiac activation sites was generated as a visual aid.

Additionally to the visualization in time of the cardiac activation sites location, the software is able to project the Pericardium Potential Maps on to a 3D FE model of the human heart surface. The model used for projection comprises only a mesh containing the heart surface geometry with no conductivity information. PPM projection was accomplished by reconstructing pericardium surface potentials the same way as the precordial leads ECG were reconstructed. For PPM projection, the coefficients for lead vectors are obtained for each one of the points of a FE pericardium model considering 20 possible dipole locations inside the heart. Using the same dipole selection process as used for the Precordial ECG reconstruction, pericardium surface potentials were reconstructed in a time- by- time basis as well. For a single time sample the dipole with the greatest magnitude was selected to reconstruct the pericardium surface potentials, as before, using a modified version of Eq. 2, namely:

$$[v]^{1329} = [c]^{1329}[m]^{1329} \tag{5}$$

Here, $[v]^{1329}$ is a column vector containing pericardium surface potentials in the 1329 points of the FE model of heart's surface, $[c]^{1329}$ is a 1329-by-3 matrix containing the coefficients for the surface potentials lead vectors, and $[m]^{1329}$ is 1-by-3 matrix containing the components for an equivalent dipole moment. Pericardium Potential Map projection was achieved by solving Eq. 5 at each time sample and then projecting the obtained surface potential values in a 3D color coded polygon-filled model of the pericardium. Since surface potentials in the PPM are updated and projected every time sample and displayed along with a Precordial lead evolution in time, a very accurate depiction of cardiac polarization patterns was obtained.

3. Results

The proposed software was tested in a population of 30 patients, 15 patients with no detected cardiac abnormalities and 15 with cardiac abnormalities. The software analyzed a complete cardiac cycle by solving the inverse problem of electrocardiography at each time sample; twenty possible dipole locations were considered simultaneously. Results were interpreted and analyzed in a patient-by-patient basis by properly identifying both graphically and numerically the location of Cardiac Activation Sites, and were complemented with the visualization in time of the PPMs.

The analysis was performed by recording the location coordinates of the strongest dipole at every time sample (Cardiac Activation Site), using the single-moving dipole model in a complete cardiac cycle for all normal patients. This was done in order to establish normal ranges for dipole localization, as shown in Table 1. For this purpose, three points of the cardiac cycle were considered as points of interest, one within each of the P-wave, QRS-Complex and T-wave. Then, for a patient, ECG normality or abnormality at a point of interest was determined by the Euclidean distance between the coordinates of the Cardiac Activation Site and the corresponding average coordinates obtained from the normal patients. If for a specific patient the Cardiac Activation site at the QRS-complex point is found far from the average location, the abnormality was said to occur at the QRS-complex, thus indicating a potential cardiac malignancy. The same criterion was applied for the P and T waves.

Results showed consistently that for normal patients major sources for electrical activity were located at the atrial region for the P-wave, at the Right Ventricle region for the QRS, and at the Bundle of His region for T-wave for normal patients.

Table 1. *Normal ranges in the location of Cardiac Activation Sites during different sections in a cardiac cycle using the single-moving dipole model. Coordinates show the locations inside the FE model of the human heart.*

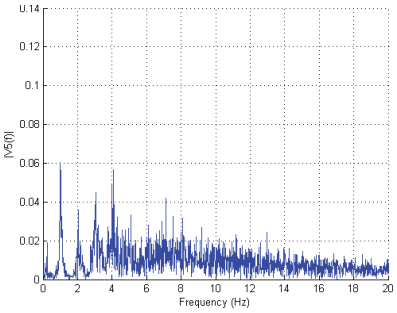
Segment of Cardiac Cycle	*Coordinates in Heart's Geometry (X,Y,Z) [mm]*	*Average Euclidean Distance for Normal Ranges [mm]*
P-wave	*(-7.33,-27.67, 382.733)*	*25.95+3.89*
QRS-complex	*(2.00,-26.47,355.88)*	*28.77+4.31*
T-wave	*(-5.00,-30.27, 373.27)*	*31.04+4.65*

Table 2. *Summary of Abnormal patients' analyses and the segments of the cardiac cycle in which a potential cardiac abnormality occurs. "In" signifies the Cardiac Activation Site location was found inside normal range; whereas "Out" means that the Cardiac Activation Site location was found outside normal ranges.*

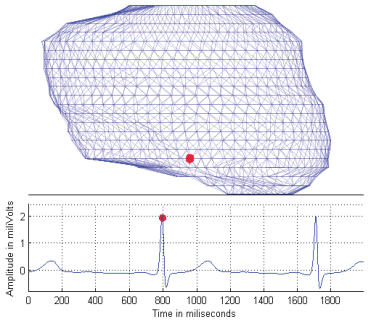
Patient	*P*	*QRS*	*T*	*Patient*	*P*	*QRS*	*T*	*Patient*	*P*	*QRS*	*T*
1	*Out*	*Out*	*In*	***6***	*Out*	*In*	*In*	***11***	*In*	*In*	*In*
2	*Out*	*Out*	*In*	***7***	*In*	*Out*	*In*	***12***	*Out*	*Out*	*Out*
3	*Out*	*In*	*In*	***8***	*In*	*Out*	*In*	***13***	*Out*	*Out*	*In*
4	*Out*	*In*	*In*	***9***	*Out*	*Out*	*In*	***14***	*Out*	*Out*	*Out*
5	*In*	*Out*	*In*	***10***	*In*	*Out*	*In*	***15***	*In*	*Out*	*In*

If at least one of the cardiac cycle segments is found to have a Cardiac Activation Site out of range, the patient was considered to present a potential cardiac abnormality. The proposed software was able to successfully identify abnormalities in 93.33% of the abnormal patients. The analysis was complemented with the visualization of the location of the Cardiac Activation Site at a specific time

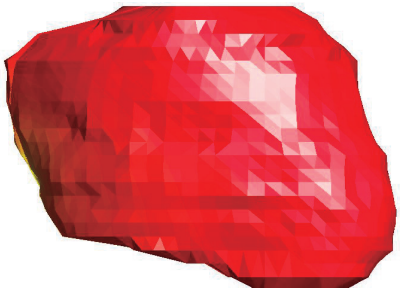
moment during the cardiac cycle, which permitted the identification of the cardiac region in which the Cardiac Activation Site was located. If for the QRS complex, the Cardiac Activation Site was found numerically out of range, one may observe where it was located inside the heart, and then determine not only that there was an abnormality but also the place where it occurred. Additionally, the diagnostician can inspect the surface potentials provided by the time - varying PPM and detect any anomaly in the pericardium polarization patterns. Spectral analysis, which is needed for wave segmentation and noise reduction in PPM reconstruction, succeeded in detecting patients' cardiac cycle duration with a 97% accuracy for all of the normal patients, whereas for abnormal cases spectral analysis successfully detected cardiac cycle duration for only 53.33% of normal patients. This discrepancy suggests that spectral analysis provides a preliminary detection of a potential malignancy, since for all normal patients a single predominant frequency component matching the real ECG signal's frequency is present while for abnormal patients the predominant frequency components are at excessively high frequencies. Figure 1, shows a typical analysis output for a normal patient and Fig. 2 for an abnormal patient.



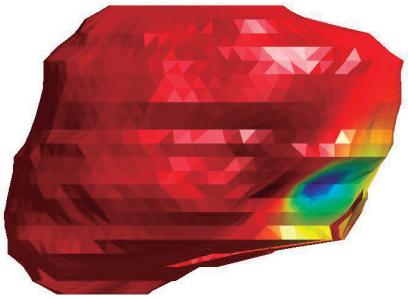
i) Spectral Analysis



ii) Dipole Location at QRS

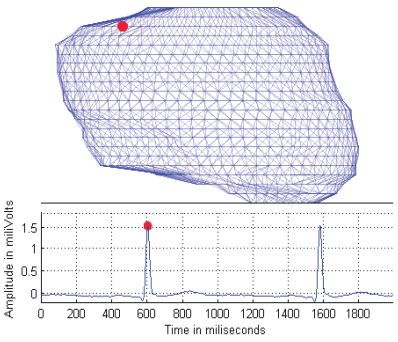


iii) Snapshot of PPM front view during QRS

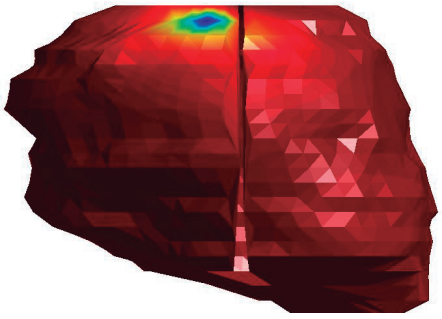


iv) Snapshot of PPM back view during QRS

Figure 1. *Analysis output for normal patient 1, showing Spectral Analysis with a predominant frequency, Cardiac Activation Site located at the right ventricle during the QRS-complex, and its color coded PPM front and back views during the QRS-complex.*



i) Dipole Location at QRS



ii) Snapshot of PPM side view during QRS

Figure 2. *Analysis output for abnormal patient 7(suffering a myocardial infarction) during the QRS-complex, showing a Cardiac Activation Site located at the atrium, which suggests an anomaly, and its color- coded PPM side view.*

4. Discussion

Given the overdetermined nature of the linear system of equations described in Eq. 2, which is by definition ill posed, the related dipole moment calculation is subject to inaccuracies. However, it was found that filtering the signal before solving Eq. 2 improves the conditioning of the problem to a great extent; this is reflected in the precision of the reconstructed ECG precordial signals. Solutions obtained in the form of dipole moment magnitudes clearly showed a single maximum dipole moment at a specific location inside the heart, which strongly suggests that the signal measured in the human torso's surface was generated in that region.

A typical analysis output yielded by the proposed software consists of: 1) a spectral analysis of the original ECG signal previous to digital filtering, 2) visualization of reconstructed signals, 3) visualization of dipole moment magnitudes at each one of the 20 possible locations, 4) analytical and visual single-moving dipole location in time and, 5) time varying PPM projected simultaneously with precordial ECG signals. As mentioned above, the spectral analysis provides a preliminary result by the detection of predominant frequency at abnormally large frequencies, which suggests potential arrhythmias. The location of the single-moving dipole, which is selected as function of its magnitude, indicates the possible source of the potential abnormality. Finally, the PPM projection permits the identification of any abnormality in the pericardium's polarization and depolarization patterns during the cardiac cycle.

The results presented in table 1, show that for all of the normal patients major cardiac activity was located in the atria region during the P-wave segment, right-ventricular region during the QRS-complex, and in the Bundle of His during the T-wave. Also, table 1 provides the mean Euclidean distance in mm of normal patients' dipole locations from the mean normal dipole location. This provides the necessary conditions for establishing normal ranges of Cardiac Activation Sites locations. Table 2 provides a summary of the analysis performed in abnormal patients, which show that abnormalities were detected in 14 out of 15 abnormal patients used for this study. The accuracy of the presented results can be greatly improved by increasing the normal patients' population since tolerance criteria in Table 1 would be reduced. Therefore, abnormalities would be more noticeable numerically. In all of the normal and abnormal cases, Cardiac Activation sites were successfully identified and their color-coded PPM showed corresponding polarization and depolarization patterns.

5. Conclusions

The proposed software properly identified potential abnormalities and their possible locations for 93.33% of the abnormal patients, except for patient in which no abnormality was detected. This leads to the conclusion that the characterization of the cardiac electrical activity with multiple possible dipole locations can lead to a reliable preliminary detection of the origin of cardiac abnormalities in the ECG. The equivalent single-moving dipole solution, along with signal reconstruction and PPM projection, proved to be valuable assets in a preliminary ECG analysis of a patient.

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