3D Reconstructions from Animal Models in the ECGi Tikhonov Estimation at Sinus Rhythm

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Abstract

The heart is a vital organ to the human body, having an excitatory system with electrical activity able to see in a electrocardiogram (ECG). The sinus rhythm is the normal conduction of stimulus, although the rhythm can be changed by some reasons resulting in an abnormal heart rhythm, like the atrial fibrillation (AF), characterized by irregular and rapid electrical signals in the atria. Studies with animals are used to improve diagnoses and treatments as such as 3D reconstructions, segmental techniques that uses 2-dimensional images to create a 3-dimensional triangular surface of the heart to understand the AF mechanisms. A rabbit heart was used as a model to generate this segmented geometry, defining the exact locations of the electrodes at the moment of the electrocardiogram, with groups of 16 electrodes in the right atrium (MEA 1), left atrium (MEA 3) and ventricle (MEA2) and 5 different resolutions of accuracy of the geometry vertices. This 3D model was compared to a Slicer segmentation of MRI images with the Dice coefficient: 0.74. The 3D reconstruction was a tool to recreate the electrical activity of the heart's epicardium, in sinus rhythm with 4.2 seconds and 8 activations, by a Tikhonov regularization in order 0 through a 60-electrode group in a tank surface around the heart, simulating the torso. The correspondent vertices of 3 selected electrodes, one in each MEA of the heart, was compared to the original signal with certain delay. Right atrium and ventricle presented good results in terms of similarity, while left atrium showed some controversial results.

1. Introduction

The human heart is considered a vital organ of the body by its blood pumping function and the central engine of the body's circulatory system. Each chamber of the heart owns one atrium and one ventricle. The atrium is called a primer pump because propel weakly the blood inside the ventricles. The ventricles supply the principal pump force of blood through the lung's circulation (right ventricle) and systemic circulation (left ventricle). The ventricular muscle is larger and thicker than the atrial muscle, contracting more forcefully in a bigger scale of duration [1].

The sinus rhythm is the usual rhythm of heartbeats, established by the sinoatrial (SA) node, delaying the stimulus to avoid the contraction of both atrium and ventricle. The cardiac excitation begins in the SA node in the right atrium, reaching the atrioventricular, propagating to the left atrium, and finishing in the Purkinje fibers in the ventricular myocardium. The electrical activity of the action potential propagate through the heart can be seen in the electrocardiogram, a recording of the electrical signals.

The atrial fibrillation (AF) is the most common sustained arrhythmia (abnormal heart rhythm) and is characterized by rapid, irregular electrical signals in the atria as a result in the conduction system of the heart, in which contraction of the atrial fibers is asynchronous so that atrial pumping ceases altogether [2].

Studies with animal model have improved over the years and applied to diagnoses and treatments in the clinical area. The 3D reconstruction is a technique created to fully comprehend the AF mechanisms. This reconstruction uses a segmentation of 2-dimensional images of the desired heart to create a customized 3-dimensional triangular surface of the heart. It divides an image into regions, delimiting structures of interest [5].

The 3D reconstruction is a fundamental tool to reconstruct the electrocardiogram of a certain subject. Visual reconstruction is a way to acquire the electrode location in coordinates used on electrocardiographic imaging (ECGi), a forward model that predicts the cardiac electrical activity through the torso [6]. The Tikhonov regularization is the most popular numerical solution for ECGi that approximates the unknown exact solution in the range of the adjoint of the forward operator [7].

The aim of this study is analyzing a recording of electrical activity of a rabbit heart at sinus rhythm and the ECGi estimation using the segmentation and the Tikhonov regularization.

2. Methods

2.1. Experimental Data

The research protocol for the experiments with animal model has been approved by the Local Committee under protocol number 3947230519. The object of study were New Zealand rabbit hearts. The rabbits were anesthetized and had their heart extracted through a sternal thoracotomy. The heart was submerged in a glass plate with a modified Krebs-Henseleit solution with reduced calcium concentration and had its tissues remains removed. Its aorta was connected in a Langendorff perfusion system which infused a modified Krebs solution to supress the mechanical contraction.

Three MEAs (Micro-Electrode Array) was connected to the heart, the first MEA was located in the right atria, the second in the ventricle and the third, and last, in the left atria. Each MEA contains 16 electrodes, receiving the electrical activity from the pericardium. The heart with the MEAs was placed inside a translucent hexagonal tank surrounded with 60 electrodes.

The process of acquisition of the images of the heart is done after the capturing of the electrophysiology of heart activity. 101 2D images obtained from 3 cameras were taken from the 360 degree- rotation of the heart through a step motor. The calibration setup contained a triangular prism with grids on its surface forming 15 landmarks in each of the three faces. The prism was placed exactly where the heart was, oriented to the cameras, and photos were captured from each face to calculate a transfer matrix, that transform the pixel coordinates into physical coordinates.

2.2. 3D Reconstruction

A 3D geometry of the heart uses the 101 2D images and the calibration data to recreate the volume of the heart utilized in the corresponding experiment. The images and the calibration data were loaded in the VSC (Visual Studio Code) so it can be performed a process of segmentation on them. The segmentation consists in a heart silhouette identification through a custom-developed software in Python and it's divided in two steps, the manual threshold and the semi-automatic refinement, where the 101 images are coloured in purple and gray shades to indicate the area of the heart, using a region of interest (ROI). The manual threshold contains a bar to adjust the purple area, and the semi-automatic refinement allows the drawing of polygons on the images to delete and insert the desired region in each image. A 3D geometry was accomplished by the mesh and smoothing of the triangular surface segmentation containing five different resolutions (20000, 10000, 2500, 1200 and HR) with different number of vertices.

To input the electrode localization in the moment of the experiment, all the three MEAs were placed in the right areas of the 3D geometry, and all the 48 electrodes were numbered and named, creating a projection.

A comparation between the triangular surface segmentation in MATLAB and a segmentation obtained from MRI images by Slicer was made in their generated morphologies, calculating the Dice coefficient.

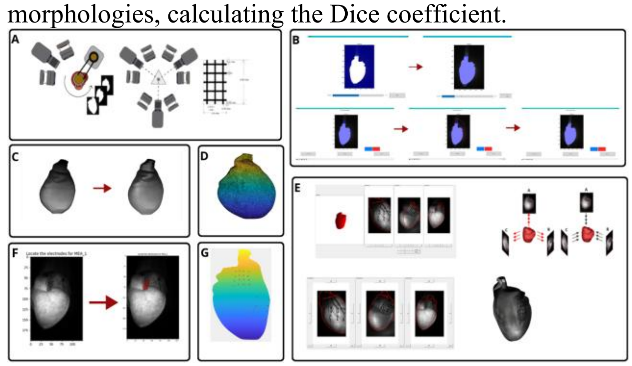

Figure 1. A: Data Acquisition and Calibration. B: Semi-Automatic and Manual Segmentation. C: Triangular Mesh Smoothing. D: Geometry. E: Geometry Projection on the Optical Mapping. F: Electrode Location Marking. G: 3D Reconstruction.

2.3. Pre-Processing

The electrical activity obtained in the experiment is extracted and filtered, passing through a process of modeling so the data appears clear and recognizable. The main object is identifying the cardiac rhythm of the heart in the specific moment and its properties.

After the electrical signal is extracted, it is filtered using initially a personalized Detrend function in MATLAB that removes the baseline drift. Then, is followed by a low-pass filtering, which is a Butterworth filter that removes high-frequency noise while preserving relevant cardiac activity according to a frequency spectrum analysis of the signal. Finally, the signals were downsampled from 4000 Hz to 200 Hz to optimize computational efficiency maintaining signal fidelity, decreasing the time of the ECG estimation. A Principal Component Analysis (PCA) function is applied only in the filtering of the tank, assuming importance of the data based on its variation, returning principal component coefficients for data, using SVD by default.

2.4. ECGi

Electrocardiographic imaging (ECGi) allows signals estimation from non-invasive metrics. ECGi is an electrocardiograph inverse method [3] to obtain epicardium potential utilizing the torso measured potential. To suppress calculation errors on the signal measures, a regularization method is applied, to set boundaries delimiting amplitudes or potential derivatives in space, time or both, limiting these parameters into electrophysiology and heart electrical camp limits. ECGi is essential to reconstruct the epicardium electrical signature utilizing the data obtained from the tank.

A personalized function in MATLAB makes use of conductivities for blood, tissues, and air and the heart and tank organized geometries to create transfer matrix that stores all their vertices and faces, where the lines are the number of vertices of the tank and the columns are the number of vertices of the heart. This matrix is computed based on potential influence and potential gradients matrix.

The signal is interpolated by a Laplacian operator, keeping the measured data. Estimation parameters need to be set for the regularization method chosen for the reconstruction. The regularization parameter selected was logspace (-0.5, -12, 10). The regularization method used in the reconstruction was the Tikhonov method with a 0 order [4].

The Laplacian interpolation fulfills the empty spaces between the tank electrodes as vertices. The electrodes position in the 3D geometry is extracted, along with their correspondent vertex in the estimated signal

3. Results and Discussion

3.1. 3D Reconstructions

Fourteen segmentations were completed, including the 3D geometry and the electrode placing. The five resolutions presented different quality and accuracy among them. The lowest resolution (1200) didn't confer good electrodes location, mixing them and changing their places. The highest resolution (HR) was the better resolution, with great projection of the electrodes. Processing time for the segmentation is about 20 to 30 minutes.

Figure 2 presents all the fourteen reconstructions and the electrode location in each region of the heart: right atria, left atria and ventricle, in interest to capture most of the heart activity as possible. Each letter from A to J shows one different heart in 3 different positions, allowing all the regions visualization.

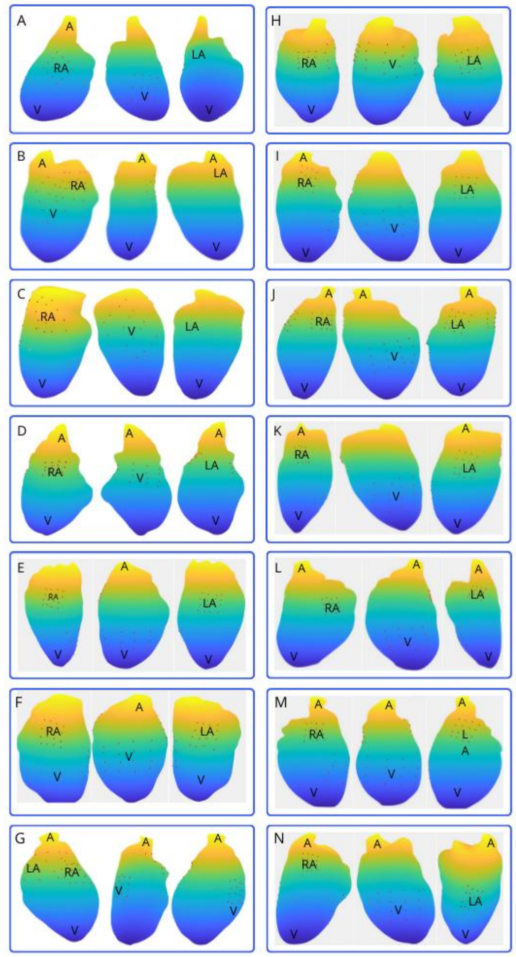

Figure 2. Fourteen 3D Reconstruction with triangular surface smoothed of a heart in the High Resolution. A: Aorta. RA: Right Atria. LA: Left Atria. V: Ventricle.

The comparation between segmentations uses the SegmentComparison module [5] to select the Slicer segmentation as a reference and the triangular surface segmentation as the compare segmentation. The software calculated the coefficient for one single geometry reconstruction, which was approximately 0.74. The software presented good result due to the Dice coefficient mechanism, which is: similarity between segmentations grows close to the number 1.

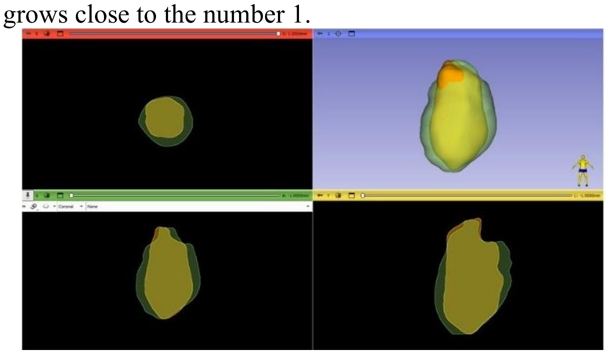

Figure 3. SegmentComparison module views.

3.2. ECGi

A different heart record of an electrical signal with a sinus rhythm with 4.2 seconds and 8 activations was selected to analyze the reconstruction by Tikhonov method. One electrode from each area of the heart was chosen, filtered in the pre-processing, and estimated. The processing time of estimation in the period of 4.2 seconds is about 50 to 60 seconds.

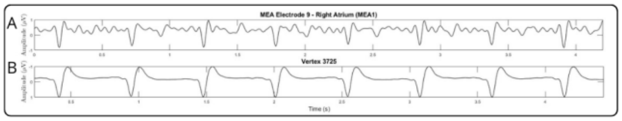

Figure 4. A: Electrode 9 from right atrium (MEA 1) filtered signal. B: Electrode 9 correspondent vertex (3725) estimated.

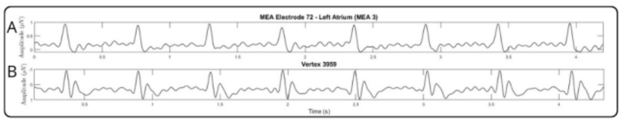

Figure 5. A: Electrode 72 from left atrium (MEA 3) filtered signal. B: Electrode 72 correspondent vertex (3959) estimated.

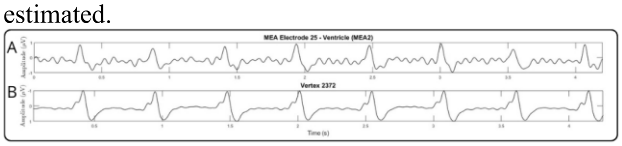

Figure 6. A: Electrode 25 from ventricle (MEA 2) filtered signal. B: Electrode 25 correspondent vertex (2372) estimated.

The estimated signal from right atrium (Figure 4.B) seemed to reconstruct the original signal (Figure 4.A) in good shape, although it was necessary to delay it in 0.23 ms to match the original one. The signal from ventricle (Figure 5) also looked very similar, also being delayed in 0.05 ms. Otherwise, even presenting similar form, the left atrium (Figure 6) didn't reconstruct the signal as good as the right atrium and ventricle, with 0.13 ms of delay. All the reconstructed signals were rotated in the x-axis.

The reason why it was delayed is that the estimation is based on the signals from the tank, which receive most of its information from the ventricle, due to the ventricles' ticker walls, bumping the blood with more strength. Therefore, the tank has a little delay from the ventricle, and bigger delays from the left and right atrium, respectively, in the sinus rhythm.

Atrial and ventricle presented good signals similarity when compared with those measured directly on the epicardium considering morphology. The shapes look similar to each estimation despite the delays and noises.

4. Conclusion

In this study, a single rabbit heart was reconstructed in a 3D model, with a geometry by a triangular surface segmentation and a proper electrode localization of the electrocardiogram moment. The 3D reconstruction was compared with a Slicer segmentation of MRI images using the Dice coefficient, showing good result. A 4.2 second sinus rhythm recording of the same rabbit heart with 8 activations was analyzed and estimated through an ECGi technique and a Tikhonov regularization. Despite the delay of the vertices' signals correspondent to the electrode's signals in the epicardium, the right atrium and left atrium presented good shape similarity. However, the left atrium estimation didn't provide such refined result. The results may be improved using different pre-processing, in the epicardium electrical activity, and pos-processing, in the estimation.

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