MODELING THE DYNAMIC HEART FOR IMPEDANCE BASED CARDIAC PATHOLOGY DETECTION

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Abstract: A computer model of the heart shape cyclic variation has been developed that provides a realistic description of the deformation of the human heart surface shape during a single cardiac cycle. The model is a particular case and cannot be easily adjusted for some other individuality. Thus, we have developed the method and toolkit, designed for fitting and visualizing adjustable analytical 3D dynamic model of the heart (*piecewise-ellipsoidal model*) with simple geometry to desired forms. As a parallel study we have also developed a system of modeling dynamic heart with spline-surfaces. This paper explains the modeling systems and techniques for evaluating the adaptive piecewise-ellipsoidal model and visualization of the local deformation of the heart models (displacement field visualization).

Introduction

Models of the dynamic processes of the human body are valuable tools for understanding the inter-relatedness of bodily functions. The dynamics of thorax anatomy due to cardiac function and breathing creates a large variation in electrical measurement results. Analysing these dynamic signals gives valuable information on the health of the subject. The signals can be of biological origin (ECG) or technology induced (impedance measurement). The measured signal will be heavily affected by the dynamics of the anatomy of the tissues but also by the dynamics of admitting properties of tissues (due to blood perfusion or air ratio in lungs and health of tissue). Computer modeling of dynamic tissues and simulation of electric signals are used in research for noninvasive health monitoring as well as for invasive and implanted devices.

Methods

Due to the lack of detailed and dynamic models of the human thorax or the heart for common pathologic conditions, a new approach is taken in dynamic heart modeling. In this work modeling of the dynamic heart is done by two approaches in parallel: 1) 3D dynamic model of the heart is composed of adjustable spline surfaces; 2) an analytical (piecewise-ellipsoidal) 3D dynamic model of the heart with simple geometry

A) B)

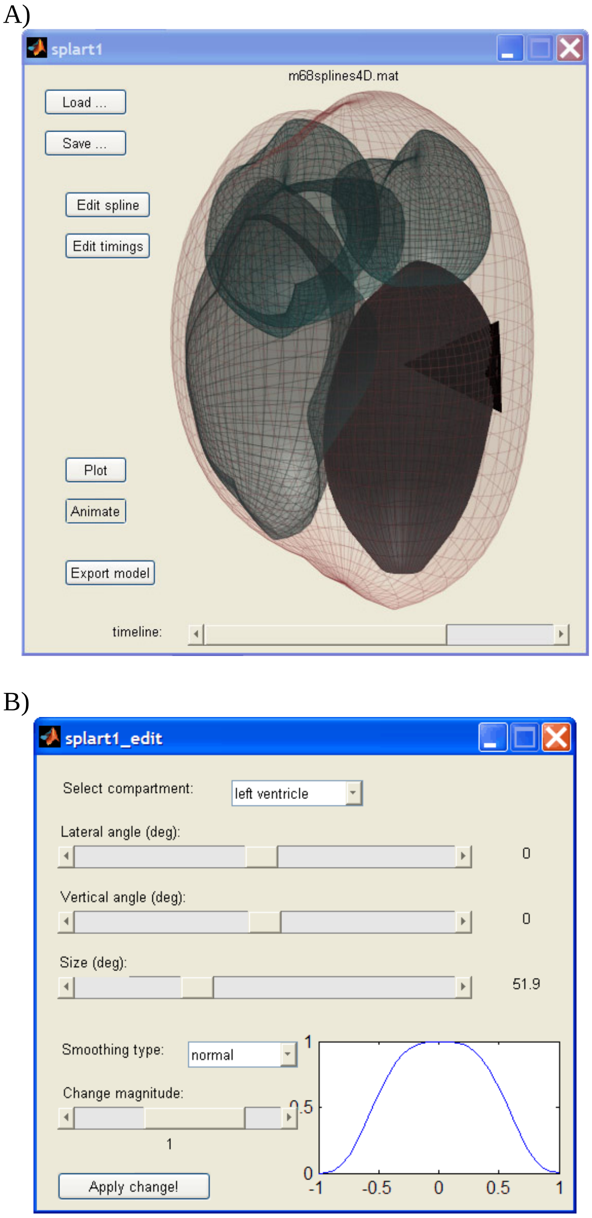

Figure 1: A) Graphic user interface for viewing and modifying the spline surfaces of heart compartments. The compartment that is being edited, is highlited, and the editable regions is shown by a cone. B) Tool for simple adjusment of surfaces, with left ventricle editing in progress

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is developed that has adjustable parameters for contraction.

In the first approach dynamic heart anatomy model has been created from segmented set of CT data. The chambers of the heart were then modelled as spline-surfaces, that are closed and smooth in 3D space as well as in time. A toolset has been created to view and easily edit the surfaces that represent heart chambers (fig. 1).

At the current stage, the first approach that uses spline-surfaces can be used for dynamic computer simulation of electric signals inside the heart. It is being used for research of impedance measurement with pacemaker catheter, that has several measurement-electrodes inside the right and/or left side of the heart. The catheter enters the heart through the vein, goes through the atrium and is attached to the tip of the ventricle (fig. 6). Impedance measurements are made between different combinations of these electrodes continuously during a heartbeat with multiple frequencies. When analysing the impedance signals it is possible to determine stroke volume of the heart. This particular modeling approach is for developing algorithms for stroke volume computation from impedance signals got inside hearts of different patients having various pathologies. With the adjustable heart model presented here, it is possible to implement all desired heart shapes, heart rates and conditions in simulation space.

In the second approach, on the basis of a set of real time MRI images and applying also physiological knowledge, a model of heart surface variation was composed . The initial MRI data for the model was obtained from [1]. The initial data comprises a movie of the heart beating: data set of 160 images taken at 10 time points for 16 parallel sections of the heart. We had to reconstruct the heart surface (epicardium) and its variation during a heart cycle without taking into account the inner structure of the heart.

For each image in this collection, corresponding contour of the heart was found. Figure 2 shows heart surface construction for a single time moment.

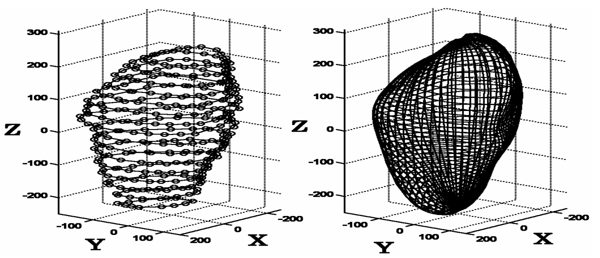

Figure 2: Composing of heart shape using spline surface. Left – collection of contours, right – obtained heart surface

By means of a spline function r = F (φ, θ) in spherical coordinates, a closed and continuous surface for each single time point was obtained. Using the described above approach, the heart shapes for all ten time moments were obtained. Counting on the dependence of the epicardium shape on time, the time coordinate was introduced. We have adjusted the model and introduced additional time moments in it, for which additional shapes also were produced. The objective was to fit the time course to the facts known from physiology. The proportions of the whole heart and distances between heart sections were also adjusted.

We expect to compose the heart shape of four simple geometrical forms. This can be a simplified approximation of the model described above. Two half-ellipsoids (to model the left ventricles and atria) and two quarters of ellipsoids (to model the right ventricles and atria) can be used as these simple geometric forms. The state with the most dilated ventricular half-ellipsoids corresponds to the end of diastole. Figure 3 shows a toolkit, designed for fitting and visualizing this analytical piecewise-ellipsoidal model to converge to a sequence of desired shapes.

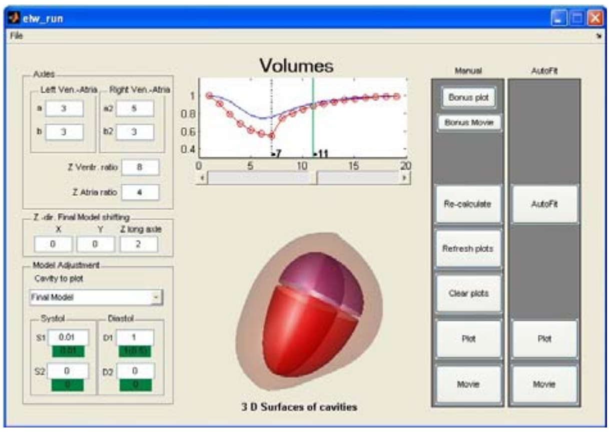

Figure 3: Toolkit designed for fitting the adaptive piecewise-ellipsoidal model of the heart (red and purple ellipsoids) to a desired shape (semitransparent pink shape)

We presume that the heart has simple geometric form and its deformations comprise “small variations“of the shape and volume. These “small variations“ would be possible to describe by four-dimensional perturbation functions. Improving the description and order of the perturbation functions, the improvement of simulation of the natural heart motion should be possible. By changing the parameters of the functions, we expect to get control over model, to be able to adjust and fit it as required.

Determination of proper parameters may be done in two ways:

a) manually, by changing set of parameters of the functions, size and positions of half-ellipsoids and quarter-ellipsoids;
b) or using automatic techniques of fitting piecewise-ellipsoidal model of the heart to desired shapes, based on *Levenberg-Marquardt* optimization.

In the process of reconstruction, the following principles are considered:

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a) We take it as a fact, that the volume of heart muscle remains constant and blood is incompressible.
b) We suppose to model a "healthy" heart, not a "badly ill" heart.

Therefore, main physiological facts (e.g., correlation between the durations of systole and diastole, proportions of heart axial and radial dimensions, known forms of volume curves, the volume changes of the heart cavities) shall remain like in a healthy human.

The movement of the heart during contraction can be studied by visualizing the displacement field between any two time moments inside cardiac cycle. The values of the normal shift of the surface were calculated as the normal projections of the increment of radius-vector r.

The end-diastolic state was taken as the reference state. Figure 4 shows toolkit designed for visualization of the local displacement of the heart surface.

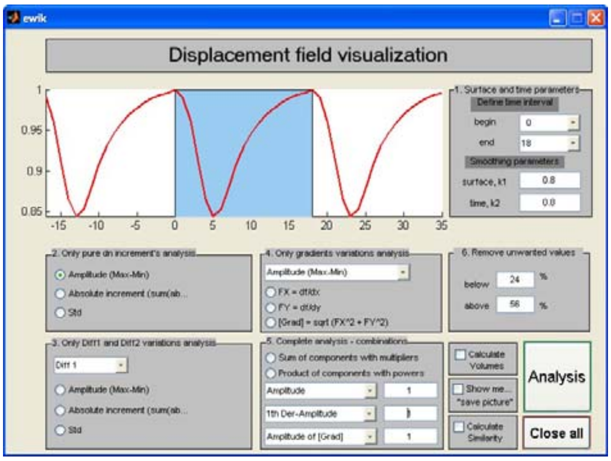

Figure 4: Toolkit designed for visualization of the local displacement of the heart surface.

By tracking for the basic variations of the heart shape, it is possible to find a reliable coefficient of applied smoothing of the heart surface.

Results

Continuing on the topic of the piecewise-ellipsoidal model, for the description of the heart shape cyclic variation, a spline function r = F (φ, θ, t) in spherical coordinates and time was chosen. By the means of spline smoothing, a closed and continuous surface for all time points was obtained.

The model was used as the tool for calculation of ventricular, atrial and total heart volumes. The obtained relative variations of total heart volume and the atrial and ventricular volumes agree with the data of Hoffman et al. [1] (8%, 18%, 5%, correspondingly).

The results of the first steps of this modeling have been successfully used for simulations of intracardiac impedance signals [2, 3] and Foucault Cardiography (FCG) [4] for tracking the heart mechanical activity. The motion of atrioventricular septum was taken into account at volume calculations.

The model of the heart shape cyclic variation was also used as a tool for studying of small variations of the heart surface. Figure 5 shows the displacement field for the heart surface. These pictures used to highlight regions on the heart surface with maximum relative motions between 24% - 100% (top), and minimum relative motions between 0% - 56% (bottom). The regions are ideal to separate contracting and expanding regions of the epicardium.

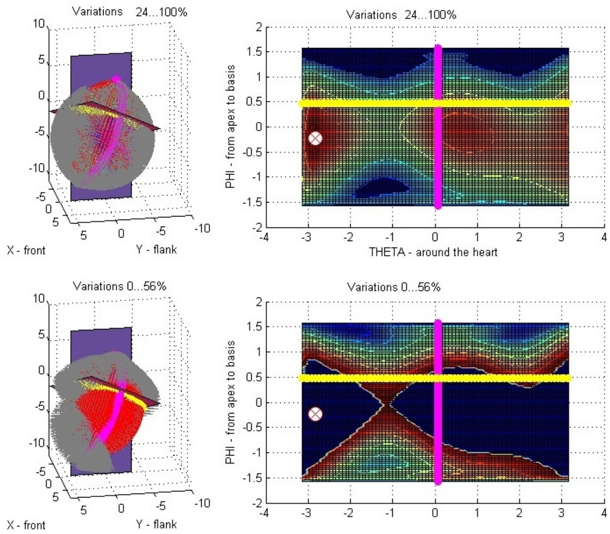

Figure 5: Local displacement field to the heart surface (left). Right: color map of displacement (the hotter is a color, the greater is the displacement

The regions with maximum motions are located on the surface of ventricles; the least motion can be found on the heart surface just above the septum between the left and right ventricles. The motion in the atrial regions is less and not so strongly marked.

The obtained model of the heart shape cyclic variation was used as a tool for deriving a collection of cuts of the exterior surface of the heart which where used for FCG studies [5].

In case of the spline-surface modelling approach, the model has been used in simulation and the results are shown as simulated impedance signals. Intracardiac impedance research is being conducted for application in implanted devices (cardiac pacemakers) [2, 3]. Frequency range of 1 kHz to 10 MHz is used in measurement practice and the simulation software supports this range for multifrequency analysis. Tissue electrical properties are frequency-dependent and will produce signals with magnitude and phase shift as a result.

In this simulation current at the frequency of 220 kHz is inserted from electrodes 1 and 4. Electrode 4 is taken as a reference with potential 0. The potentials in the whole simulation space are calculated on every timeframe. 12 timeframes have been used to simulate one heart-beat in this case. Although a lot higher

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temporal resolution can be exported from the toolset because of the smooth nature of the spline-based model and used in simulation when necessary. Impedance change is shown (fig. 6) based on the inserted current and calculated potentials at the locations of the electrodes 1, 2 and 3. Notably phase angle also exhibits variability during the motion of the heart.

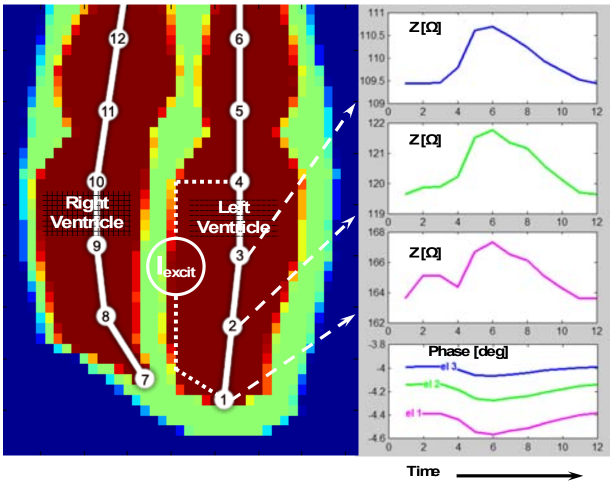

Figure 6: Simulated impedance signals from three different electrodes inside the left ventricle of the heart during heart-beat. 12 frames have been used for impedance calculation. Phase angle changes according to the volume also

Discussion

We have developed an empirical model of the heart shape cyclic variation where the modeled heart surface is closed and smooth and gives a possibility to track the variations of the heart surface. Generally, it looks well and is reliable. Basic features of the variations of the heart shape are detected. Total heart, ventricular and atria volume variation are in good correspondence with the facts, known from physiology.

But problems still remained. With the piecewise-ellipsoidal model of the heart shape cyclic variation and time course of the heart motion are a particular case and cannot be easily adjusted for some other individuality. This model omits the inner structure of the heart and the connections to the great blood vessels. Motion of the heart in the thorax due to breathing is not described. Small uncorrelated heart surface oscillations that are located near the base and the apex of the heart still remain. Those shortcomings are easily overcome by the spline model, but this toolset yet lacks the monitoring and parameterization capabilities of the ellipsoidal modeling system.

In connection with the piecewise-ellipsoidal model, a principal question appears: which functions of the heart must be taken as controllable? By introduction of various extra adjustable parameters it ought to be possible to better fit existing heart form to desired sequence of shapes.

Conclusions

Volume calculations and visualizations of the heart motion demonstrated usefulness of our visualization toolkits for exploring of heart models. Color maps of displacement give a good overview of the heart surface variation distribution. Spectrum markers can be used to indicate isocontours in the visualized field and color maps are useful for revealing structures such as symmetries and discontinuities.

The developed toolkits and visualization systems will be used as the basis for progressive approximation of the adaptive models.

Both modelling approaches have their strengths and weaknesses. Still both are full solutions for building dynamic heart models for use in simulation. Next logical step would be to combine the best features of both modeling systems to create a package of fitting and improving tools of parametrized heart simulation. This unified solution would be a very valuable tool for conducting further research on cardiac impedance.

Acknowledgement

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