A Functional Heart Model for Medical Education

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We developed a 3D computer graphic model of functional anatomy of the human heart. The model provides visually correct anatomical and functional detail suitable for medical education. We reconstructed 3D surface models of the human heart based on segmentation obtained from the Visible Human image datasets. We developed a fiber based muscle action model specially adapted for the myocardium. Each muscle fiber is equipped with contractile and elastic elements and is used as a local shape deformation guide. The timing of fiber contraction activation is driven by patient specific action potential excitation patterns. As a first step we have visualized the function of a healthy heart. We are now planning to visualize a range of cardiac conditions and dysfunctions.

1 Anatomic Model

The reconstruction of a 3D surface model of the human heart was based on the Visible Human Project datasets [1]. Segmentation was extracted from the axial anatomical cross-section images of the Visible Male and Female datasets in the thoracic region (see figure 1). A male and female heart models were reconstructed. The male model, coming from a 39 year old healthy person, was used to visualize the function of a healthy heart. The female heart model, coming from a 59 year old person with enlarged heart, will be used for the visualization of heart failure.

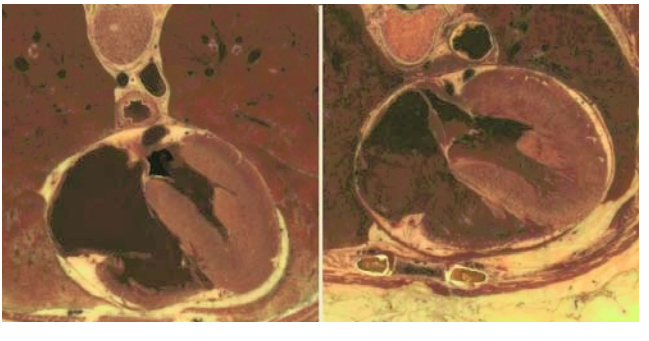

Fig. 1. Axial anatomical cross-section images from the Visible Male (left) and Visible Female (right)

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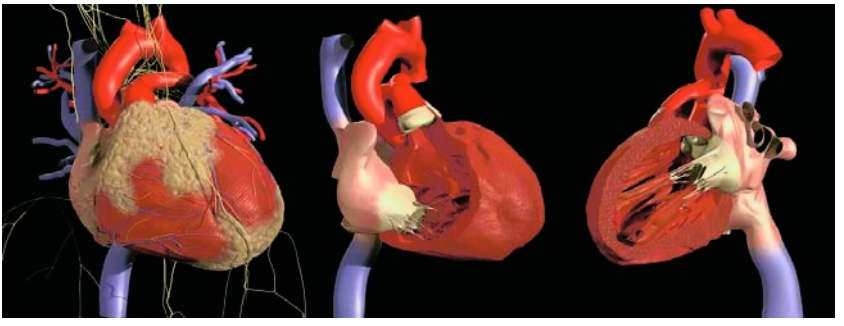

Fig. 2. Views of the reconstructed 3D female heart model

At every stage of development particular attention was paid to the functionality of each part of the model. This was done to facilitate the integration of the graphic model into the functional model.

The surface model includes detailed inner and outer wall structures on all four chambers and valves. Also structures such as the trabeculae carneae, the papillary muscles and all the main cardiac veins, arteries and fatty tissue have been modeled (see figure 2).

2 Mechanical Contraction

We developed a fiber based muscle action model specially adapted for the human heart myocardium [2]. In our model a muscle is represented by a set of fibers, which run through the muscle body.

Each fiber is equipped with contractile and elastic elements connected in parallel [3] (see figure 3). Each fiber line acts as a local shape deformation guide for the surrounding muscle tissue. By activating each fiber we can accurately specify the level of contraction and volume preservation of a muscle.

The modeled fibers in and around the ventricles were made to follow approximate heart muscle fiber orientation data obtained from diffusion tensor MRI [4] (see figure 4).

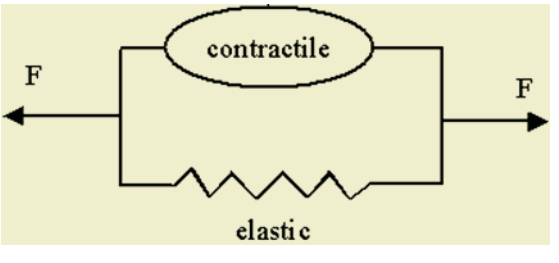

Fig. 3. Muscle action model with parallel contractile and elastic elements

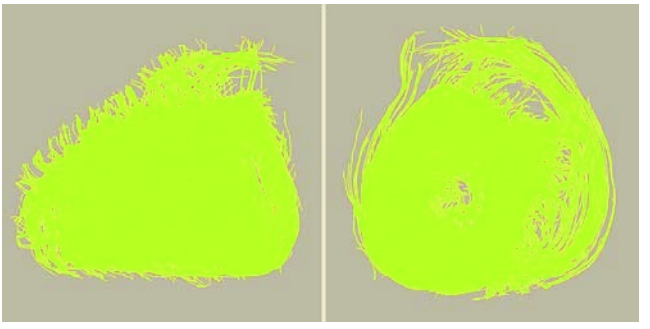

Fig. 4. Muscle fiber orientation in both ventricles

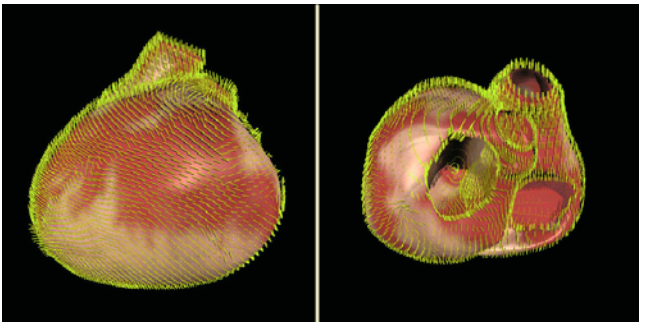

Fig. 5. Muscle fiber orientation mapped onto the 3D model

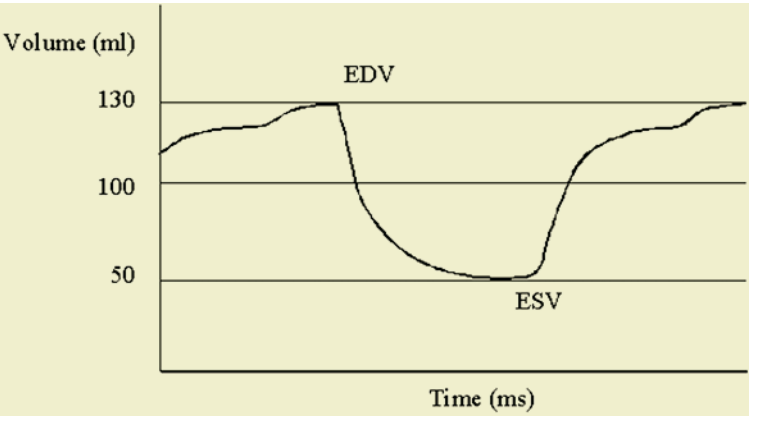

Fig. 6. Graph of the inner volume of left ventricle during a normal heartbeat cycle

Fiber orientations were geometrically mapped onto the inner and outer surfaces of the ventricle models. Thus the surface of each ventricle was equipped with the fiber

based deformation system (see figure 5). Fiber orientation in the atria was derived from anatomical morphology studies [5] and by cadaveric observation.

The mechanical model was equipped with an inner volume calculation algorithm. An experimental relationship between the amount of fiber contraction and the inner volume in a heart chamber (i.e. the left ventricle) was derived as follows: the amount of fiber contraction was step increased and the resulting inner chamber volume was simultaneously calculated. By reversing this experimentally derived relationship a simple volume graph such as the one in figure 6 was used to determine the amount of mechanical contraction during a complete heartbeat cycle (see figure 7).

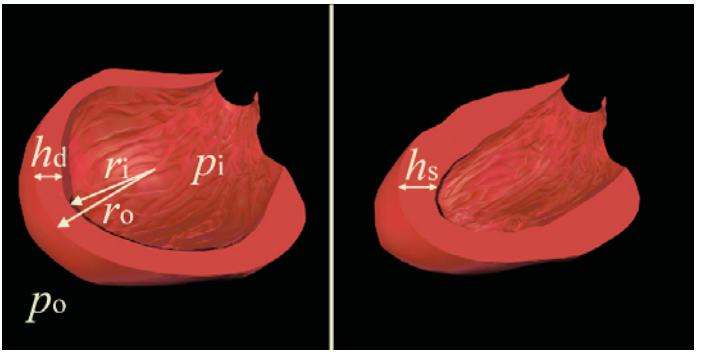

Fig. 7. Wall thickness in the left ventricle in end diastole h_d (left) and end systole h_s (right)

The ventricular wall thickness was calculated by locally approximating the chamber in question (i.e. the left ventricle in figure 7) with the shape of a spherical membrane with thick walls. In this case, the law of Laplace (see equation 1) relates the inner and outer pressures p_i and p_o and radii r_i and r_o with the membrane stress T [3]:

$$T = p_i r_i^2 - p_o r_o^2 / (r_i + r_o). \quad (1)$$

$$T = h(\sigma). \quad (2)$$

The inner pressure was made to follow a pressure graph of a normal heartbeat cycle while the outer pressure was kept constant and approximately equal to the atmospheric pressure. Equation (1) was combined with an experimentally acquired stress (T)/strain ($h(\sigma)$) function of cardiac muscle [3] (see equation 2). The wall thickness was calculated by combining equations (1) and (2) and solving for h.

All four main valves (bi-cuspid, tri-cuspid, aortic and pulmonary) were modeled. Fiber based rigging enabled their opening and closing function, synchronized with the heartbeat cycle (see figure 8).

Cardiac vessels (coronary arteries and veins) were subjected to forced displacement by the underlying muscle contraction, while their volumes were kept constant (see figure 9).

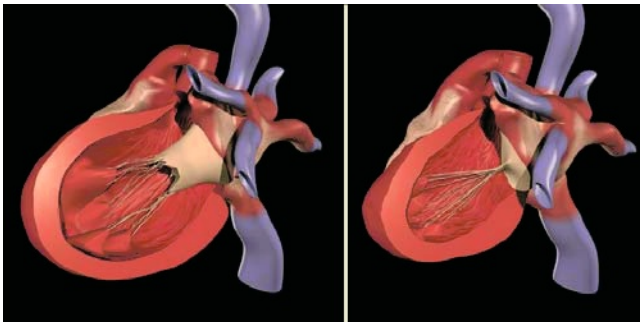

Fig. 8. Left ventricle in cross-section and bi-cuspid (mitral) valve during diastole (left) and systole (right)

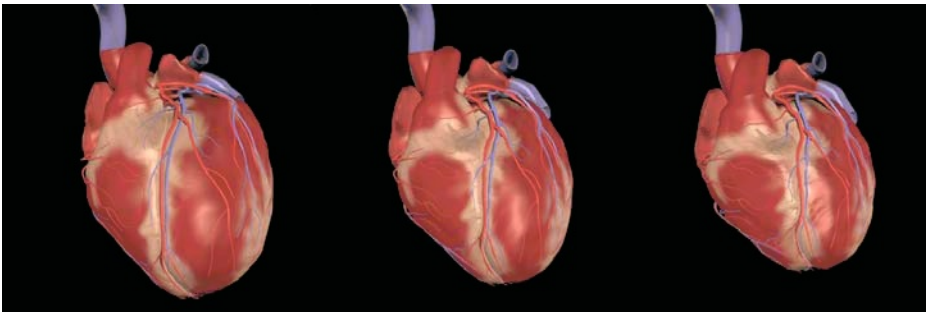

Fig. 9. Cardiac vessels during heartbeat from end diastole left to end systole right

3 Electrical Excitation

The timing of fiber activation can be driven by manually designed contraction/time graphs. All movement in atria, ventricles and valves can be independently driven by such graphs. By modifying the contraction/time graphs we can visualize normal heart beat as well as various arrhythmic conditions.

Patient specific action potential maps were also used to drive the timing of the mechanical model. In figure 10, electrical propagation maps were acquired using the Ensite catheter (from Endocardial Solutions Inc.) inside a patient's right atrium.

In a cardiac cell mechanical contraction occurs after the cell has been electrically stimulated. Each peak of electrical stimulation is followed by a single contraction peak with an approximate delay of 150 ms (see figure 11).

The above mentioned patient specific maps were geometrically projected onto the 3D surface of our modeled atrium (see figure 12). The mechanical contraction of the right atrium was activated by patient specific electrical data. Muscle contraction at each point on the atrium peaked approximately 100-150 ms after the arrival of maximum action potential on the same point.

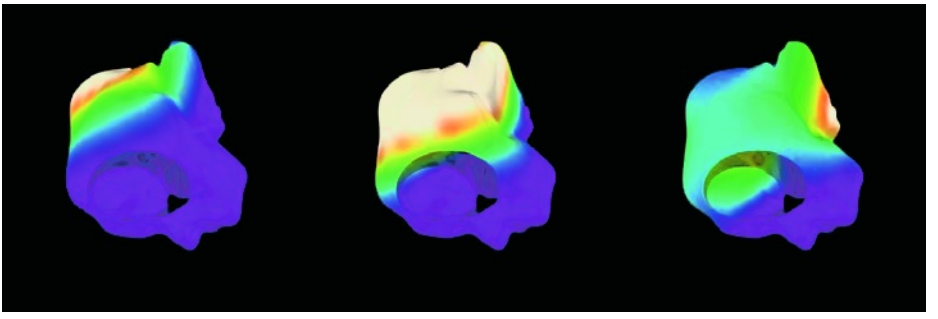

Fig. 10. Patient right atrium geometry with recorded electrical activation pattern

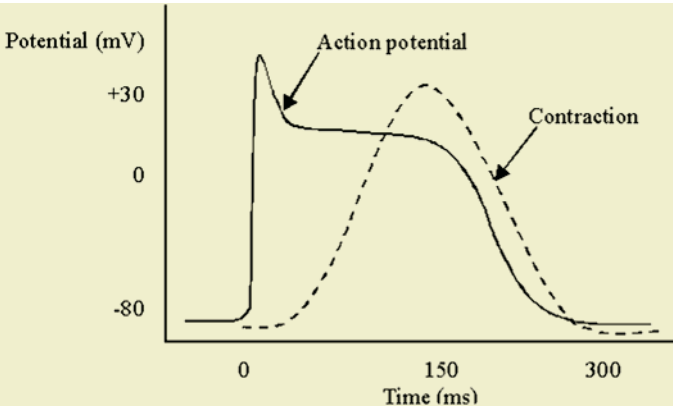

Fig. 11. Graph of action potential and contraction in a single cardiac cell (contraction graph out of scale)

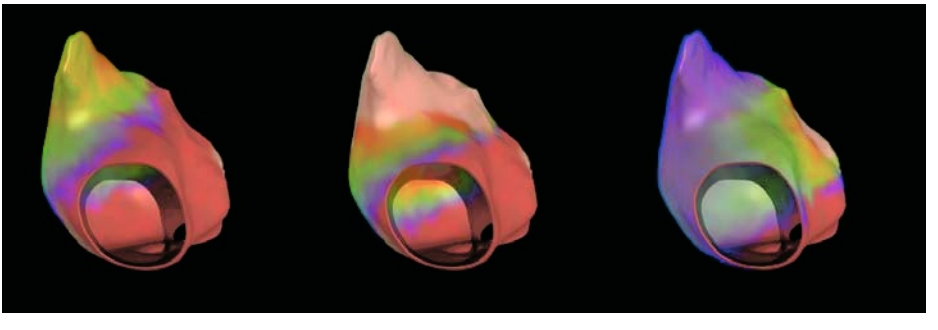

Fig. 12. 3D heart model right atrium with mapped electrical activation pattern

4 Conclusion and Future Work

A heart function visualization model was developed. A fiber based muscle action model was combined with inner volume/time and pressure/time graphs in order to

achieve a visually correct contraction cycle. Manually derived and patient specific electrical data were used to activate the model. As a first step we visualized the function of a healthy heartbeat in 4 dimensions. As a further step we are planning to visualize a range of cardiac conditions and dysfunctions such as myocardial infarction, atrial fibrillation, bradycardia, tachycardia, the sick sinus syndrome, valve dysfunction, etc. Also the transition between arrhythmic and normal cycles will be addressed. This research is supported by a SMART Exceptional Award grant from the Department of Trade and Industry, UK.

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