A customizable aortic root and left ventricle model

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Abstract

Physical simulations can help in surgery planing, as many questions can be answered before operation. In case of valve-preserving aortic surgery a patient specific heart model should be simulated, as idiosyncrasies can significantly influence the final blood flow. In this paper we present an anatomically based left ventricle and aortic root model, which can be customized based on parameters that can be extracted from medical imaging data. Our model is a spline based surface, that can be tessellated and fed as an input to a physics simulation. We pay special attention to ventricle animation as it defines the basic characteristics of blood outflow to the aortic root. We also created an interactive 3D application, where model parameters can be defined in an intuitive way, and provide instant feedback of the resulting heart model.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Modeling packages

1. Introduction

During valve-preserving aortic replacement the patient's valve tissues are placed inside a synthetic aortic root. It has never been proved exactly how the exact position of the re-implantation of the valve tissues influence the final blood flow after surgery. Our goal is to simulate the blood flow in the replaced aortic root with the implanted valves to examine different configurations, which could help decision making before surgery.

To do this it is essential to precisely model the anatomic structures of the valves and their surroundings. Modelling of the left ventricle is also important, as the opening of the aortic valves is controlled by the blood pumping of the left ventricle. Closing is also induced by the suction effect of the expanding ventricle. This paper describes our parametric heart model which will be used in later simulations.

2. Human heart anatomy

To model the anatomic structures we must understand the functioning of the human heart. Heart cycle can be divided into two main phases, the contracting (systole) and the relaxation phase (diastole). Heart functions influencing aortic valves can be described briefly as the following. During the relaxation of the left ventricle the blood arrived from the lungs flows from the left atrium to the left ventricle. At this moment the mitral valve separating the atrium and the ventricle is in its open position, while the aortic valves are closed. During contraction the mitral valve closes, the aortic valve opens and blood is pumped from the left ventricle to the ascending aorta. The sub phases of the heart cycle will be described in more detail later, but for modelling the anatomy it is enough to examine the two extremes: the totally con-

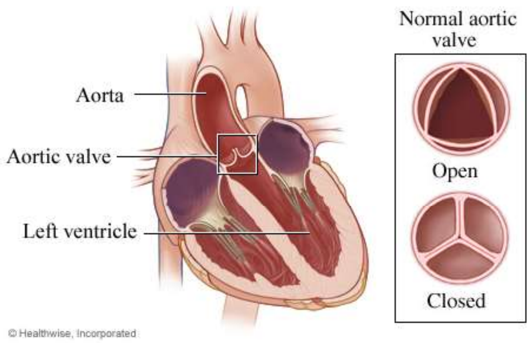

Figure 1: *The anatomy of the human heart.*

tracted left ventricle with open aortic valves and the totally expanded left ventricle with closed aortic valves.

Figure 1 shows the structure of the human heart as well as the two extreme state of the aortic valves. We can conclude that to model the function of the aortic valves we don't need to model the whole heart, it is enough to model the ascending aorta, the aortic valves and their surroundings (sinus of Valsalva) and the inner walls of the left ventricle. We considered the modelling of the mitral valve as well, but finally we modelled them as a fully open or closed disc where blood can flow through at open stage.

During simulation it is important to create a patient specific model, thus our model should be customizable by patient specific parameters. These parameters will be extracted from medical imaging data such as CT or MRI, preferably in an automatic way [5]. The three dimensional geometry of the simulated heart will be generated automatically from these parameters. Thus we had to define the basic anatomical features of the left ventricle and the aortic root that can be served as modelling parameters. Though several illustrations can be found in literature about the structure of human heart, exact anatomical formations are hard to define.

The final representation of three dimensional model is defined by the needs of the simulation method to be used later. We found that most of the fluid and deformable geometry simulation techniques can work on polygonal meshes [7], thus the final model should be convertible to this representation.

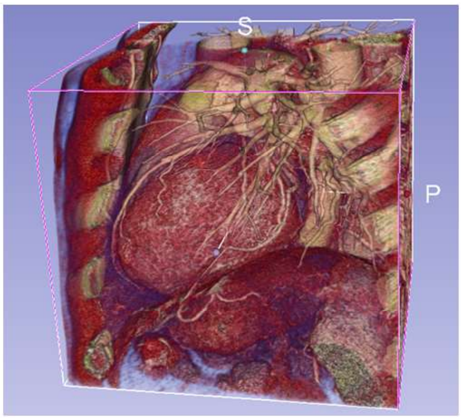

Figure 2: *Volume visualization of a heart CT using Slicer3D.*

3. Preliminary heart model

To become familiar with the exact structure of the aortic root and the left ventricle we extracted a triangular geometry from a CT data. CT data capture high resolution images at a time (Figure 2). Functional CT are not as common, and have low time resolution. On the other hand two CT data at the two heart cycle extrema can well define the geometry.

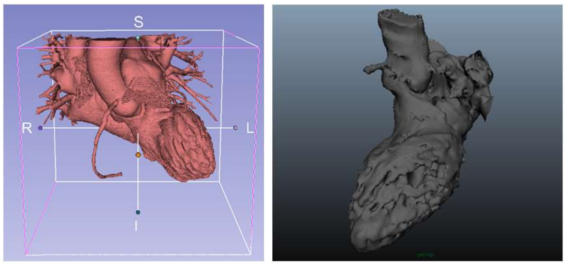

Figure 3: *Segmented CT data (left) and its cleaned tessellated geometry (right).*

We extracted a triangular mesh from a healthy patient's CT data. We used region growing segmentation to isolate the blood inside the left ventricle and the ascending aorta. As the CT data was captured with injected contrast material the structures filled with blood could be well identified (Figure 3).

Our next step was to import the tessellated geometry to a 3D modelling package for further clean up. After region growing there will be areas that are filled with blood but not important for us, so these triangles were deleted. After tessellation we have an anatomical model with fine details, but the triangle count is just too high for physical simulation, thus we have to decimate the geometry (see Figure 3). Though the tessellated geometry has high quality it is noisy

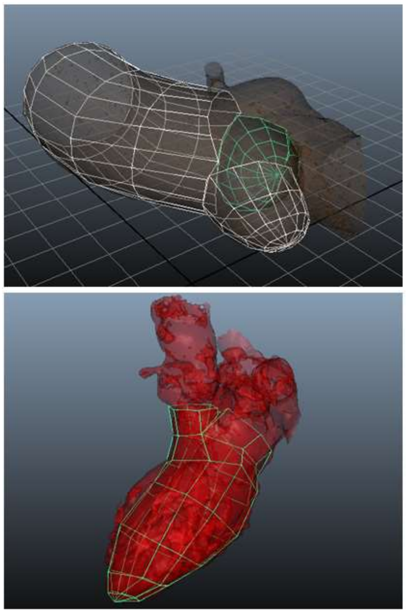

Figure 4: *Simplified aortic root and left ventricle geometries.*

Name	Type	Default Values	Description
mitralValveCenter	3D vector	(0, -16, 14)mm	The center of the mitral valve
mitralValveRadius	float	16 mm	The radius of the mitral valve
ventricleTipPointDias	3D vector	(-26, -80, -43) mm	Apex position in diastole
ventricleTipPointSys	3D vector	(-26, -63, -43) mm	Apex position in systole
ventricleMaxRadiusDias	float	25 mm	Maximal ventricle radius in diastole
ventricleMaxRadiusSys	float	16 mm	Maximal ventricle radius in systole
ventricleMaxRadiusHeight	float	0.5	Position of maximal radius on main heart axis (0-1)

Table 1: *Left ventricle modelling parameters.*

and at certain areas it is incomplete (e.g. the thin tissue of the aortic valve can not be captured).

To create a simplified and cleaned geometry we used re-topology tools to define new geometry right on the surface of the high resolution segmented triangular mesh, thus we can define new topology while the main shape is preserved. This is a common work flow in computer animation industry. Figure 4 shows the simplified geometry of the aortic root and the left ventricle. During geometry simplification we encounter several questions like what are the exact shape of the aortic valves or where the mitral valve is exactly located. These question can be answered only with anatomical knowledge.

Using triangular mesh description has a disadvantage that it is hard to parametrize. Geometric deformation techniques could be well used for the ventricle, but would perform poorly on the sharp edges of aortic valves. As the parameters that control the geometry should be extracted from the medical data we moved toward an anatomic model and used splines to define the geometry. The model parameters extracted from medical data directly control the spline control points, and the final triangular geometry is tessellated from the spline model. However our preliminary segmented triangular model helped a lot to plan the topology of the spline model, and could be used for later validation.

The next sections describe our ventricle and aortic root models, their parameters, and how they influence geometry.

4. Left ventricle model

The exact shape of the the left ventricle has high variations among patients. The inner wall of the ventricle is highly ribbed and has a complex surface. This makes identifying feature points for model parameters very hard, so we have to construct a simplified model. Most of the papers in previous work define the ventricle as an ellipsoid, so we followed a similar approach. We approximated the geometry near the apex as an ellipsoid-like surface and constructed connector surfaces to the circles of the annulus and the mitral valve.

The final shape of the ventricle will be controlled by the center and the radius of the mitral valve and the annulus, the apex in systole and in diastole and a maximal ventricle radius in systole and in diastole. To construct the ellipsoid shape we need a main axis. This will be defined by the apex and the center of the mitral valve. This means that this axis is changing as the apex changes its position during one heart cycle.

The position and orientation of the annulus will not change as we fix our coordinate system to the aortic root. We also fixed the mitral valve position, but its orientation needs to be defined. We found that the plane of the mitral valve is perpendicular to the main heart axis. As this axis changes its

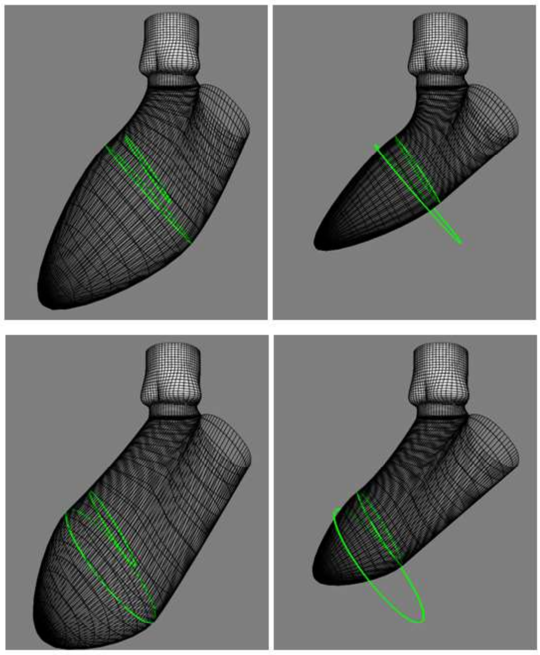

Figure 5: *The effect of changing the maximum radius height ventricle model parameter on the ventricle geometry. The top row shows the average model (systole on the right and diastole on the left), bottom row shows the modified geometry.*

direction we defined the mitral valve plane as the average of the planes perpendicular to the main heart axis, and fix this orientation during the whole heart cycle. A final parameter that can be set is the position of the largest ventricle radius along the main heart axis.

The final modelling parameter set is listed in table 1 with their type, default values and brief description. As an example figure 5 shows the effect of the maximum radius heigh parameter on the geometry.

In case of the ventricle we should also model its movement. This is why some parameters must be given in the two extrema. The actual geometry of the ventricle will be computed from the systole and diastole models using linear interpolation. The next section describes how the actual value of the interpolation parameter should be computed for a heart cycle.

5. Left ventricle animation

The expansion and contraction of the heart has a typical pattern which is controlled by the cyclic electrical activity in the heart muscles. The cyclic movement starts with the contraction of the atria. The depolarization of the left and right atrium starts from the sinoatrial (SA) node located in the right atrium. This depolarization causes the contraction of the atria, this moment can be clearly identified as the P wave on the electrocardiogram (Figure 6). The SA node sends a depolarization wave to the atrioventricular (AV) node which causes the contraction of the ventricles. This is the QRS wave on the electrocardiogram. The AV node activates the ventricles with a 100ms delay to let the atria contract. During the contraction of the ventricles the atria re-polarize and thus relax. The final stage is the re-polarization and relaxation of the ventricles, which is depicted as the T wave.

Using the electrocardiogram we exactly know when contraction and relaxation happens, but don't know the exact rate of these movements. Fortunately we can find other measurements in literature that can help us. One such quantity is ventricle volume. Figure 6 also shows the ventricle volume change in one heart cycle. Examining this curve we can more refine the heart cycle to the following phases:

- Constant ventricle volume systole. We start from the maximal ventricle volume. The aortic valves are closed, blood flows from the atrium to the ventricle until the pressure inside the ventricle exceeds the pressure inside the aortic root. In this short phase the volume of the ventricle does not change, only the pressure rises. Duration is 0.05 sec (interval 0.0s - 0.05s).
- Blood outflow. Here begins the contraction of the ventricle and the opening of the aortic valves. It has two subphases: a rapid and a slow contraction. The contraction is caused by the work of the ventricle muscles. Duration is 0.25 sec (interval 0.05s - 0.3s).
- Constant ventricle volume diastole. In the first phase of diastole ventricle volume does not change only ventricle pressure decreases. As the back flow of the blood from the arteria closes the aortic valves, ventricular pressure starts to decrease until it reaches the value of the atrial pressure. Thus mitral valves can open. Duration is 0.1 sec (interval 0.3s - 0.4s).
- Blood inflow. As the mitral valves open the refill of the ventricles starts. This phase can also be divided into two: a rapid and a slow volume expansion. In this phase blood flows in passively and only fill 80 percent of ventricle volume. Duration 0.3 sec (interval 0.4s - 0.7s).
- Final ventricle expansion and blood inflow. As the atrium contracts blood is pressured into the ventricle which results in a rapid final ventricle volume expansion. This inflow takes at most 20 percent of the ventricle volume. Duration 0.1 s (interval 0.7s - 0.8s).

The described volume change can be given with a piecewise defined continuous function. Increasing and decreasing segments are approximated with square root and square functions:

$$\hat{V}_{rel}(t)|t \in (0s, 0.8s) = \begin{cases} 1 & t < 0.05s \\ (\frac{0.3-t}{0.25})^2 & 0.05s < t < 0.3s \\ 0 & 0.3s < t < 0.4s \\ 0.8\sqrt{\frac{t-0.4}{0.3}} & 0.4s < t < 0.7s \\ 0.8+0.2\sqrt{\frac{t-0.7}{0.1}} & 0.7s < t \end{cases} \tag{1}$$

Of course this function does not define the overall ventricular volume, but a relative volume change, which is the volume change between the smallest and the largest ventricle volume. This is why it has values from zero to one, which means the smallest and largest volumes respectively. The final volume is given by the following expression :

$$V(t) = V_{systole} + \hat{V}_{rel}(t)(V_{diastole} - V_{systole})$$

where $V_{diastole}$ and $V_{systole}$ are the smallest and largest ventricle volumes. Figure 7 shows the relative volume change given by the above expression.

Now that we know how ventricle volume should change over time, we only have to know how the linear interpolation parameter influences the volume of our model. As our model is a free triangular mesh tessellated from a spline surface, no analytic formula exist to calculate its volume. The volume of an arbitrary closed triangular mesh can be calculated with sums of signed tetrahedral volumes [4].

We sample the heart cycle interval and in each sample we determine the interpolation parameter that corresponds to the preferred ventricle volume. We store these parameter values and later use them for animation fitting a piecewise linear function on them. Thus at any given time we know

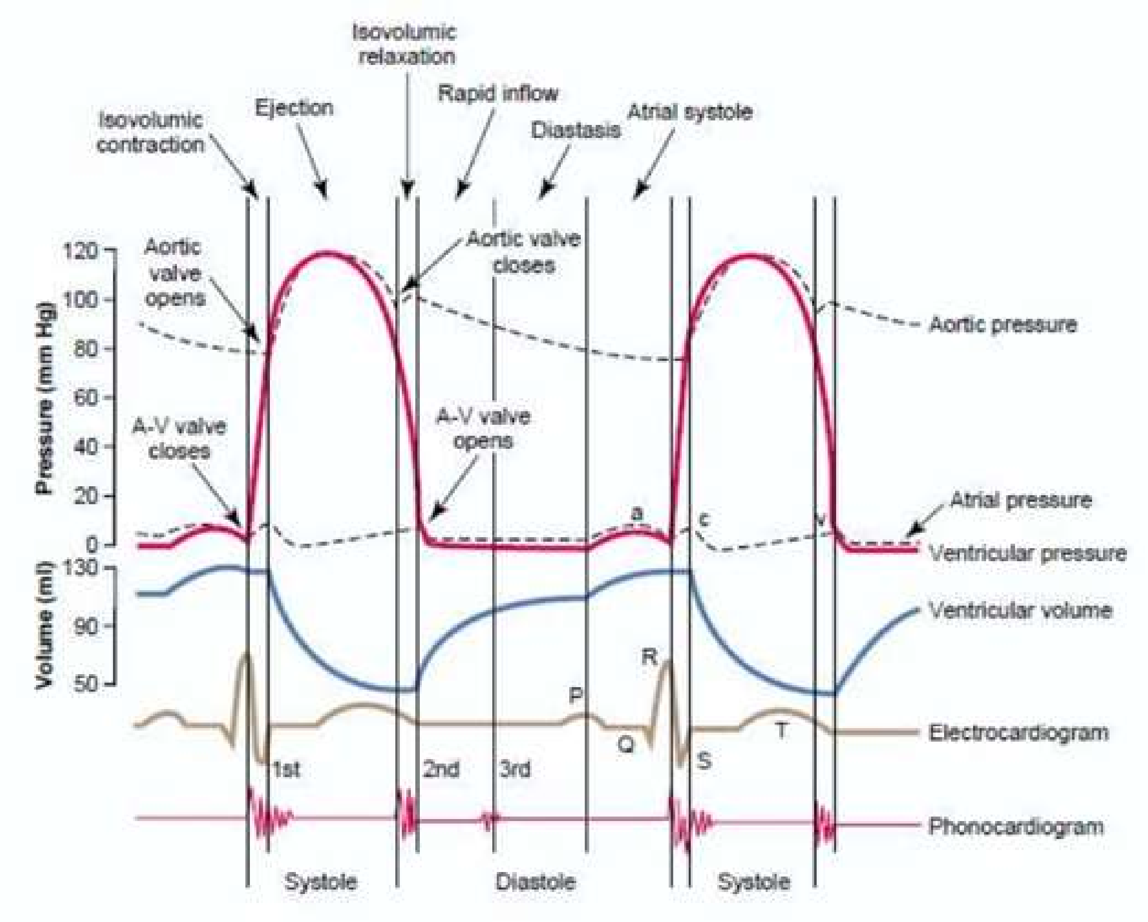

Figure 6: *Ventricular volume and pressure change.*

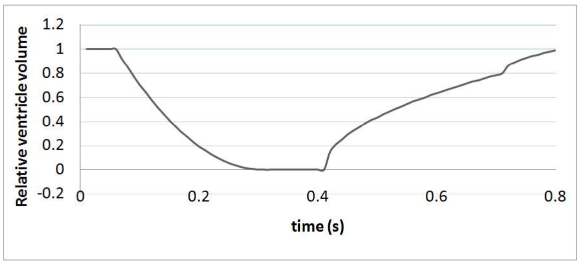

Figure 7: *Relative ventricle volume change during a heart cycle.*

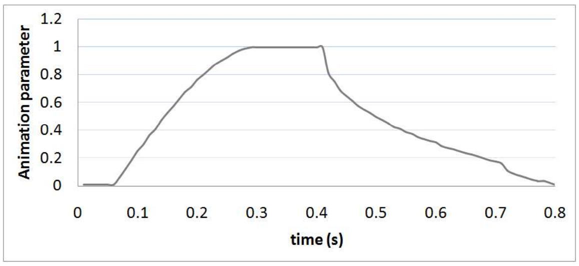

Figure 8: *Animation parameter values during a heart cycle.*

how to combine the two extreme geometry. Figure 8 shows the values of the animation parameter in a heart cycle for our average heart model.

We had to make sure that not only the relative volume changes reflect real-life average values but the overall volumes too, thus our expanded and relaxed volumes should correspond to the measured average systole and diastole volumes of real-life patients. Fortunately we can find measurements of average volumes for both male and female in literature [6]. The average contracted and expanded volume of the ventricle is approximately 50 ml and 120 ml respectively.

Our average model has 51 and 118.45 ml volume, which suggests that our model is exact.

6. Modelling the aortic valve and its surroundings

Our aortic root model is also based on a spline surface, where spline control points are controlled by anatomical features. Many articles can be found that deals with aortic valve anatomy [3], but for us the work of Calleja et al. [1] proved to be the most useful. Here we could find various anatomic measurements and average values of the aortic root.

The aortic valves are located in the lower thickened part of the ascending aorta called aortic root. Each valve has its own cavity called the sinus of Valsalva. The roughly circle shaped section where the aortic root and the left ventricle connects is called annulus, which is signed with c on Figure 9. The center and radius of this circle can be well identified on CT and even on lower resolution MRI data so these will be our first model parameters.

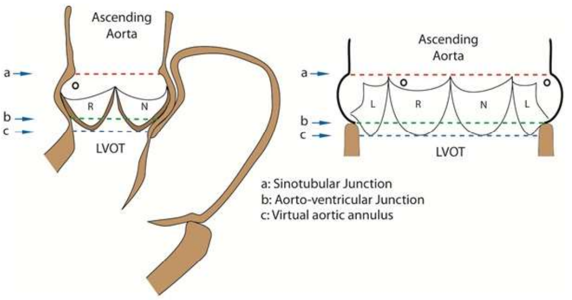

Figure 9: *The anatomy of the aortic root* [2].

Note that in our model the aortic root defines our coordinate system where the xz plane is at the annulus and y points in the direction of the ascending aorta.

The round shaped connection between the aortic root and the ascending aorta is called sinotubular junction (STJ) (label a on Figure 9). The topmost suspending points of the aortic valves (commissures) are located at this level. These commissures can be well identified on medical data, and they also define the center and radius of the STJ. The commissures are not placed evenly on the circle of the STJ, their angles are patient specific and will play a dominant role in our simulations.

Aortic valves are little pockets with sharp edges at the top, which join in a single point when the valves are closed. This point can also be identified in CT data. We placed the lowest points of the valves symmetrically between two commissures at the level of the annulus.

If the above parameters are given, the valves can be constructed, but we need some extra parameters for the sinus of Valsalva. The largest radius of the aortic root and its position along the y axis should also be given. We also introduced parameters to control the curvature and slope of sinuses.

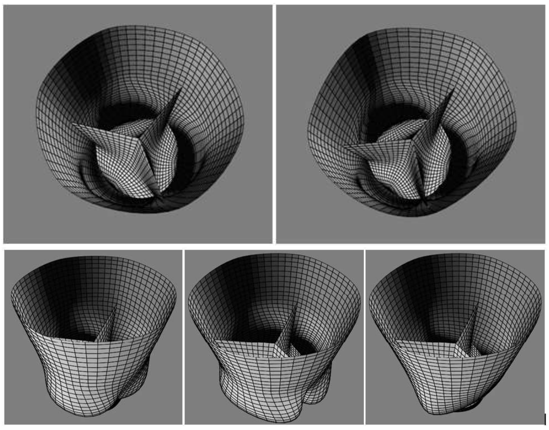

Figure 10: *The effect of changing aortic root parameters. Top row shows the average model(left) and the model with modified commissure positions (right). Bottom row shows the averaged shape sinus of Valsalva (left), a Valsalva with higher slope parameter (middle) and a Valsalva with higher curvature parameter(right).*

The final modelling parameter set is listed in table 2 with their type, default values and brief description. As an example figure 10 shows the effect of some aortic root parameters on the geometry.

7. Heart modeller application

To be able to visually design a heart model we created an OpenGl based interactive 3D heart modelling application. Figure 11 shows a screenshot of our application. The model parameters can be set with a user friendly interface. When the user changes the parameters the geometry can be recalculated. Animation parameters can also be calculated if all the modelling parameters are given. The user can also play a looped heart cycle animation. Parameter visualization, wireframe rendering and solid rendering can be turned on or off as desired.

The application has its own human readable and editable parameter file format. We can load and save these model parameter files. The final polygonal geometry is exported as a series of .obj files, which is a widely supported 3D model format. Some meta data is also saved with the models, like which vertices are fixed during simulation, or the animation parameter curve.

8. Conclusions

We demonstrated our controllable left ventricle and aortic root model. Our model is anatomically based, controlled by

Name	Type	Default Values	Description
commissure1	3D vector	(0, 17.5, 13.44)mm	Common suspension point of the L and N valves.
commissure2	3D vector	(11.64, 17.5, -6.72)mm	Common suspension point of the R and N valves.
commissure3	3D vector	(-11.64, 17.5, -6.72)mm	Common suspension point of the L and R valves.
leafletTipPoint	3D vector	(0, 15.03, 0)mm	Valve intersection point.
annulusRadius	float	11.58 mm	The radius of the annulus
valsalvaRadius	float	14 mm	The largest radius of the aortic root
valsalvaMaxRadiusHeight	float	0.25	Position of maximal radius on aortic root axis (0-1)
ostiumR	3D vector	(0, 14, -14.2) mm	Base point of right coronal ostium
ostiumL	3D vector	(-12.2, 14, 7) mm	Base point of left coronal ostium
valsalvaSlope	float	0.05	Slope of the sinuses of Valsalva
valsalvaCurvature	float	3	Curvature of the sinuses of Valsalva

Table 2: *Aortic root modelling parameters.*

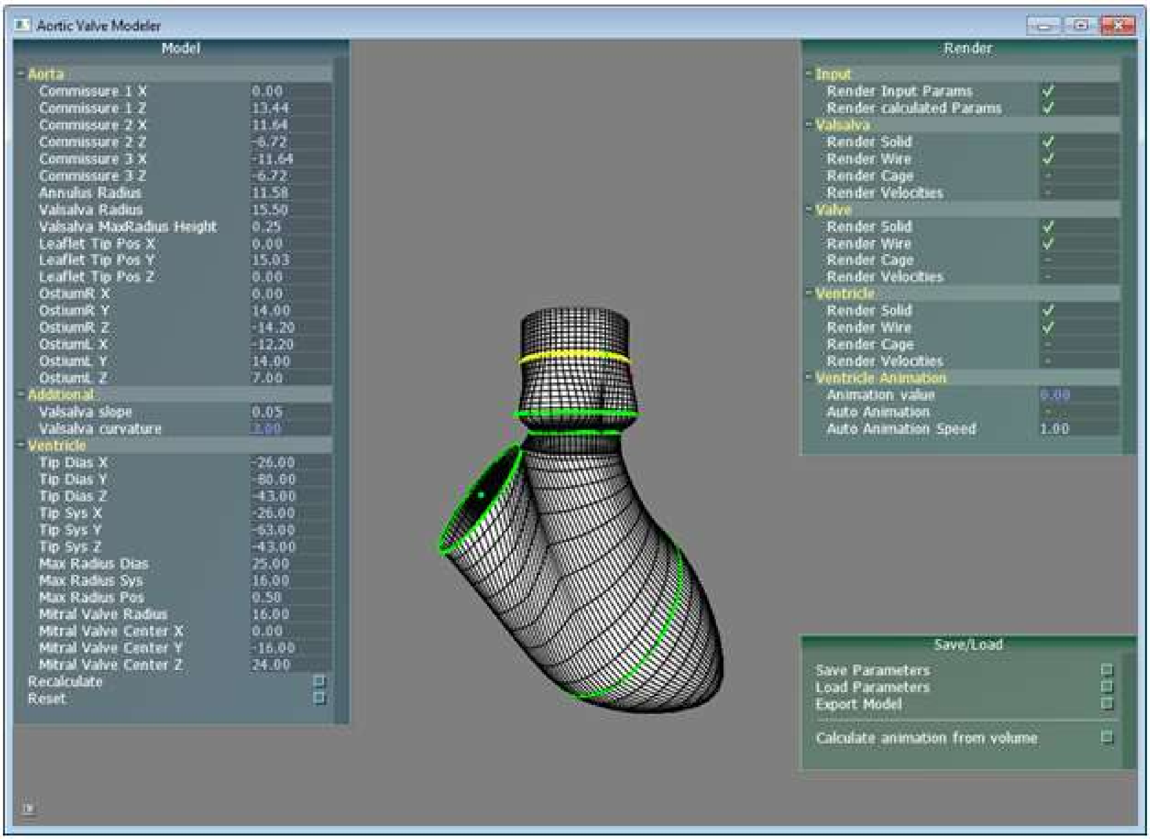

Figure 11: *Heart CT.*

parameters that can be extracted from medical data, and can be exported to a triangular mesh with preferred tessellation quality. We also showed how to animate the left ventricle realistically by fitting its volume change curve to real-life measurements. We created an interactive modelling application which will serve as a handy tool for future model design.

The output of our application can be used directly as an input of our future simulation software.

Acknowledgements

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