Aortic Valve and Ascending Aortic Root Modeling from 3D and 3D+t CT

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ABSTRACT

Aortic valve disorders are the most frequent form of valvular heart disorders (VHD) affecting nearly 3% of the global population. A large fraction among them are aortic root diseases, such as aortic root aneurysm, often requiring surgical procedures (valve-sparing) as a treatment. Visual non-invasive assessment techniques could assist during pre-selection of adequate patients, planning procedures and afterward evaluation of the same. However state of the art approaches try to model a rather short part of the aortic root, insufficient to assist the physician during intervention planning. In this paper we propose a novel approach for morphological and functional quantification of both the aortic valve and the ascending aortic root. A novel physiological shape model is introduced, consisting of the aortic valve root, leaflets and the ascending aortic root. The model parameters are hierarchically estimated using robust and fast learning-based methods. Experiments performed on 63 CT sequences (630 Volumes) and 21 single phase CT volumes demonstrated an accuracy of 1.39mm and a speed of 30 seconds (3D+t series) for this approach. To the best of our knowledge this is the first time a complete model of the aortic valve (including leaflets) and the ascending aortic root, estimated from CT, has been proposed.

Keywords: physiological valve modeling, model based quantitative & visual assessment

1. INTRODUCTION

Ascending aortic root aneurysm is a frequent form of aortic valve diseases, particular among the elderly population. It causes dilation of the sinotubular junction, which is the most frequent cause of aortic insufficiency preventing the leaflet cups to coat during end diastole (regurgitation). Thus it is apparent that ascending aortic root disorders effect aortic valve anatomies. In order to capture the entire spectrum of aortic valvular disease characteristics one must model the ascending aortic root as well as the aortic valve. Moreover ascending aortic root aneurysm requires valve-sparing operations, where the aortic root is remodeled. Such operational interventions are highly complex, often causing complications during or post interventions and current clinical assessment techniques are lacking sufficient functionality to support the physician properly.

The majority of aortic valve models in current literature are focused on either hemodynamic studies or evaluation of prosthetic valves. Ionasec et al. proposed a method to provide patient specific assessment, however the approach was not capable to model ascending aortic root disorders, due to its limited root length.

In this paper we introduce a new framework for modeling both the aortic valve and ascending aortic root using a novel point distribution model able to provide more accurate point correspondences than NURBS parametrized models and incorporates fast and efficient anatomies (root-leaflet, leaflet-leaflet) intersection handling. A weighted PCA shape model, extended with additional anatomical measurements (mean commissure distance, commissure-hinge distance), is incorporated to constrain the shape space. The ascending aortic root represented by a PDM variable length is estimated by a fast and robust shape constrained 3D circle detector. Comprehensive experiments performed on 63 dynamic 3D+t and 21 static 3D CT data-sets containing a wide variety of aortic valvular disorders evince robustness, effectiveness and speed of our approach to estimate a personalized model of the aortic valve and the ascending aortic root.

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2. AORTIC VALVE AND ASCENDING AORTIC ROOT MODELING

We introduce a novel joint physiological model of the aortic valve and the ascending aortic root. The aortic valve is defined using nine key anatomical landmarks: three commissures, three hinges, three leaflet tips and two coronary ostia (see figure 1).

![Figure 1. Aortic valve and ascending aortic root model. (a) shows a generic model of the aortic valve including nine anatomical landmarks. (b) is showing our point distribution model of the aortic valve root and leaflets including its defining hinge and commissure planes. (c) demonstrates the ascending aortic root model. (d) joint model of aortic valve (root+leaflets) and ascending aortic root.]

2.1 Aortic valve root and leaflets

The aortic valve root is constrained by the commissure and hinge planes and represented as an open surface mesh model. The valvular leaflets, using a surface mesh model as well, are attached to the root and each one is defined by two commissures, one hinge and one leaflet tip. Our model is able to handle anatomical inconceivable intersections of anatomies, such as leaflet-leaflet and leaflet-root intersections, using efficient collision-detection and collision-avoidance algorithms. Precise point correspondences on the cylindrical surface are assured due to specific resampling patterns along normals, considering the specific aortic valve curvature (see Fig. 1 (b) ).

2.2 Ascending aortic root

The ascending aorta is constrained by the commissure plane incorporating variable ascending aortic root vessel lengths (see Fig. 1 (c) ). The same resampling method as for the aortic valve root is used to resample the vessel surface accounting for vessel bending in order to achieve proper point correspondences used to build a point distribution model. The upper plane is depicted after boundary detection.

3. ESTIMATING MODEL PARAMETERS

A hierarchical estimation approach is utilized to deduce model parameters of the aortic valve and the ascending aortic root. The concept is exposed in Fig. 2.

3.1 Similarity transform and Landmarks

At first the aortic valve is approximated using a bounding box, parametrized by a similarity transform $\Theta = (x_1, x_2, x_3, q_1, q_2, q_3, s_1, s_2, s_3)$. Thereby $(x_1, x_2, x_3)$ characterizes the spatial location of the aortic valve, $(q_1, q_2, q_3)$ are a quaternion representation of its rotation in 3D and $(s_1, s_2, s_3)$ symbolize scaling factors along the local coordinate axis. The nine parameters are estimated using the Constrained Marginal Space Learning concept (cMSL) in combination with Haar and Steerable Features. Landmarks are estimated using Trajectory Spectrum Learning.
3.2 Surface Model

Boundary estimation is done in two stages. First, boundary delineating of the aortic valve root and leaflets is estimated and second the surface of the ascending aortic root. Finally anatomical important measurements can be extracted from the surface model.

3.2.1 Aortic Valve Root and Leaflets

The aortic valve root and leaflets mesh model is initialized using a mean shape deformed by the thin plate spline (TPS) interpolation, estimated from nine anatomical landmarks. A boundary detector is trained using PBT and steerable features to deform the initialized mean surface along its normals. The preliminary surfaces are projected into a shape space using a weighted PCA active shape model\(^7\) in order to impose geometrical smoothness. In addition to shape points, statistical (aortic valve root height, mean valve diameter) and anatomical measurements (mean commissure distance, mean hinge distance, commissure-hinge distance) are embedded in the shape model of the aortic valve root. During model retrieval the shape space is more constrained on the statistical and anatomical measurements, using a small number of modes and iteratively increasing the number of PCA modes and lower the measurement constraint. Finally we build a histogram of the valve interior and exterior intensity distribution and use an optimal threshold to refine the boundary in a small range along the surface normal.

3.2.2 Ascending Aortic Root - Circle Tracking

The ascending aortic root is estimated by outlining the ascending aortic centerline, which is bounded by the commissures center and following performing shape constrained circle tacking. A robust centerline position detector is trained using PBT and Haar features where positive and negative samples are generated in circular form during the training phase out of surface annotations. Throughout detection an incremental approach is applied searching 3D center points on a series of successively updating planes (see Fig. 1 (c) ). Ascending aortic root center-points are equidistantly sampled along the detected centerline. At each location, a local coordinate system is constructed, using the center-points tangent and projected right commissure landmark to indicate the orientation. The previous detected ring, starting with the commissure ring is projected to the local coordinate system and a boundary detector is applied along ring points normals. Statistical shape features (diameter) from the detected points are calculated and an iterative concept of alternating boundary detection and PCA projection by constantly decreasing weights on the statistical shape feature and increasing number of PCA modes is used to delineate the shape of a circle. Based on the ascending aortic root interior and exterior intensity histogram, an optimal threshold is derived and ring points are corrected within a small displacement.

Figure 2. A survey of our hierarchical model estimation schema.
4. EXPERIMENTAL RESULTS

We evaluated our method using 63 multi-phase cardiac CT and 21 single phase CT data sets. One multi-phase series consists typically of 10 volumes, which sums up to 651 CT volumes in total. The scans are acquired from different patients with various cardiovascular diseases (including 10 with ascending aortic root aneurysm). The CT data sets are acquired using different protocols, resulting in volumes with 80 to 350 slices and 153x153 up to 512x512 voxel grid resolution and 0.28mm to 2.0mm spatial resolution. We separated our data set in a training (80%) and a test set (20%). Evaluation results are given in table 1.

<table>
<thead>
<tr>
<th>Error measures</th>
<th>mean error [mm]</th>
<th>median error [mm]</th>
<th>90%[mm]</th>
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<tbody>
<tr>
<td>box (similarity transform)</td>
<td>4.05</td>
<td>3.75</td>
<td>5.94</td>
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<tr>
<td>landmarks</td>
<td>2.61</td>
<td>2.71</td>
<td>3.11</td>
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<tr>
<td>aortic valve surfaces</td>
<td>1.22</td>
<td>0.89</td>
<td>1.43</td>
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<tr>
<td>ascending aortic root</td>
<td>1.57</td>
<td>1.13</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Table 1. Quantitative evaluation. Box error represents the Euclidean distance between the detected and ground-truth corner points of the box. Landmark error is defined as the mean Euclidean distance between the detected landmarks and ground truth. Aortic valve surfaces error and ascending aortic root error represent the mean mesh-to-mesh error between the ground-truth surfaces and the detected one. Beforehand ground-truth and detected ascending aortic root are truncated so their shapes have the same centerline length.

5. CONCLUSION

In this paper we proposed a novel personalized model for quantitative and qualitative evaluation of the aortic valve and the ascending aortic root from both 3D+t CT sequences and 3D CT volumes. It is capable to outline the full anatomy and dynamics needed to characterize a large spectrum of aortic valve disease characteristics. In addition, we propose a fast and robust estimation schema. Its hierarchical approach using state of the art machine learning algorithms enables us to estimate a patient specific model with an accuracy of 1.39mm in less than 30 seconds. Automatic model-based measurements of the ascending root provides precise selection of proper morphology for valve sparing operations and the possibility to perform post-intervention evaluation. Future work will focus on adopting our approach to different modalities.

REFERENCES