Paper Title: Semi-automatic aortic valve tract segmentation in 3D cardiac magnetic resonance images using shape-based B-Spline Explicit Active Surfaces

Authors: Sandro Queirós^{1,2,3,4}, Pedro Morais^{1,2,3,5}, Jaime C. Fonseca⁴, Jan D'hooge^{3,*}, João L. Vilça^{6,*}

¹Life and Health Sciences Research Institute (ICVS), School of Medicine, University of Minho, Braga, Portugal.

²ICVS/3B's - PT Government Associate Laboratory, Braga/Guimarães, Portugal

³Laboratory on Cardiovascular Imaging and Dynamics, Department of Cardiovascular Sciences, KU Leuven, Belgium

⁴Algoritmi Center, School of Engineering, University of Minho, Guimarães, Portugal

⁵Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial, Universidade do Porto, Porto, Portugal

⁶2Ai - Polytechnic Institute of Cávado and Ave, Barcelos, Portugal

* Joint last authorship

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Abstract (250)

Accurate preoperative sizing of the aortic annulus (AoA) is crucial to determine the best fitting prosthesis to be implanted during transcatheter aortic valve (AV) implantation (TAVI). Although multidetector row computed tomography is currently the standard imaging modality for such assessment, 3D cardiac magnetic resonance (CMR) is a feasible radiation-free alternative. However, automatic AV segmentation and sizing in 3D CMR images is so far underexplored. In this sense, this study proposes a novel semi-automatic algorithm for AV tract segmentation and sizing in 3D CMR images using the recently presented shape-based B-Spline Explicit Active Surfaces (BEAS) framework. Upon initializing the AV tract surface using two user-defined points, a dual-stage shape-based BEAS evolution is performed to segment the patient-specific AV wall. The obtained surface is then aligned with multiple reference AV tract surfaces to estimate the location of the aortic annulus, allowing to extract the relevant clinical measurements. The framework was validated in thirty datasets from a publicly available CMR benchmark, assessing the segmentation accuracy and the measurements' agreement against manual sizing. The automated segmentation showed an average absolute distance error of 0.54 mm against manually delineated surfaces, while demonstrating to be robust against the algorithm's parameters. In its turn, automated AoA area-derived diameters showed an excellent agreement against manual-based ones (-0.30 ± 0.77 mm), being comparable to the interobserver agreement. Overall, the proposed framework proved to be accurate, robust and computationally efficient (around 1 sec) for AV tract segmentation and sizing in 3D CMR images, thus showing its potential for preoperative TAVI planning.

Summary (100)

In this study, a semi-automatic algorithm using the shape-based B-Spline Explicit Active Surfaces (BEAS) framework is presented for aortic valve (AV) tract segmentation and sizing in 3D cardiac magnetic resonance images. It combines intensity and shape-based features within a dual-stage BEAS evolution to accurately delineate the AV tract wall, followed by an automatic detection of the aortic annulus (AoA) to extract relevant clinical measurements. The algorithm was validated in thirty CMR images, proving to be accurate (around 0.5 mm against manual delineation), robust and computationally efficient (nearly 1 sec), and therefore interesting for AoA sizing prior to AV replacement interventions.

Additional information

The present submission corresponds to original research work of the authors and has never been submitted elsewhere for publication.

Description of purpose

Acquired aortic stenosis (AS), a condition in which the aortic valve (AV) calcifies and obstructs the blood flow from the left ventricle to the aorta, is the most common valvular heart disease in the elderly.¹ Among the different treatment options available, transcatheter AV implantation (TAVI) has become an effective and widely used treatment option for patients with symptomatic, severe AS and high operative risk.¹ During this minimally invasive percutaneous intervention, a prosthetic valve is delivered inside a catheter and deployed under imaging guidance at the level of the aortic annulus (AoA), without removing the native damaged valve. Because no direct access to the valve exist during TAVI, accurate preoperative AoA sizing is crucial to identify the patient-specific best fitting prosthesis to be implanted. Nowadays, it is largely accepted that 3D imaging techniques are superior for such assessment.² Among the available modalities, multidetector row computed tomography (MDCT) is frequently considered the standard, with echocardiography and cardiac magnetic resonance (CMR) imaging being radiation-free alternatives.²

To help clinicians perform the AV assessment and AoA sizing, a multitude of segmentation algorithms has been

previously presented. Nonetheless, most of these solutions focused on MDCT and, in less extent and more recently, 3D echocardiography. Among CMR-based strategies, past studies have focused on a two-dimensional assessment³ and/or disregard its application for AoA sizing and pre-TAVI planning.^{4, 5}

Recently, our team has proposed an AV tract segmentation algorithm for 3D transesophageal echocardiography (TEE) images using the shape-based B-Spline Explicit Active Surfaces (BEAS) framework⁶ – a deformable model strategy that combines the computationally efficient BEAS framework with the flexible parametrization and regularization of shapes given by statistical shape models (SSM). Since then, this algorithm has been extended towards a fully automatic strategy for AoA sizing in 3D-TEE.⁷ Since MDCT is often used within the TAVI workflow, an adapted version of this segmentation framework has also been presented for these datasets.⁸

Given the potential of 3D CMR images for AoA sizing during preoperative TAVI planning, in this study, we adapt the previously presented segmentation framework for an accurate and robust semi-automatic assessment in volumetric CMR images.

Method(s)

Overview: In brief, the proposed semi-automatic framework is divided into three main modules (Figure 1): (1) the initialization (Figure 1A), in which an average-shaped AV wall surface is fitted to two user-defined points at the AV lumen; (2) an automatic shape-based BEAS segmentation (Figure 1A), where a SSM of the AV wall is combined with intensity features in a dual-stage energy evolution to accurately delineate the AV tract; and (3) an automatic AoA plane detection (Figure 1C), in which the Iterative Closest Point (ICP) algorithm is used to align multiple reference surfaces to estimate the location and orientation of the aortic annulus. In the end, the AoA plane is used to slice the AV tract surface and extract meaningful clinical measurements, including the annular area, perimeter or eccentricity index (EI).

Initialization: To initialize the AV wall surface required to start the segmentation, the user inputs two points at the AV lumen during run-time: one at the ascending aorta and another at the left ventricular outflow tract (purple points in Figure 1A). An average valve-shaped surface is then fitted to these points (blue surface in Figure 1A).

Shape-based BEAS segmentation: A two-stage evolution of the shape-based BEAS algorithm is applied, as described in Queirós *et al.*⁶ The principle is to apply a threshold-based evolution to obtain a coarse segmentation, followed by a localized region-based evolution to refine it. In the threshold stage, the initialization surface is evolved according to the intensity at the surface points' location - it radially grows if the intensity is higher than a threshold or shrinks if lower. Given the variability in image intensities found in 3D CMR images, the threshold was defined automatically by computing the 15th percentile of the intensity values of the voxels found within the initialization surface. Upon coarsely delineating the AV wall, a signed localized Yezzi (SLY) energy is used to locally refine the segmented surface. This energy evolves the surface by searching bright-to-dark transitions, which in 3D balanced steady state free precession CMR images correspond to the boundary between the AV lumen and its wall. During both stages, besides the intensity-based term, shape-based features are employed to constrain the surface's longitudinal profiles to an AV-like shape using a one-dimensional SSM (created from manually delineated ultrasound volumes). These features decrease the algorithm's sensitivity to the overall image quality or the presence of artifacts. Specifically, two regularization terms are used: one confines the segmented profiles to shapes familiarly seen in the SSM and the other penalizes according to the profile's degree of likelihood. For further details about these algorithms, the reader is kindly referred to the original publication.⁶

AoA plane detection: Upon segmenting the AV tract, the goal is to automatically identify the AoA level to

Figure 1 - Overview of the proposed AV tract segmentation and sizing framework for 3D CMR data.

estimate the annular size. Hereto, the ICP-based strategy proposed by Queirós *et al.*⁷ is applied. In short, the principle is to align the patient's surface with a multitude of reference surfaces for which the location/orientation of the annulus plane is known. The alignment of each reference gives a prediction of the plane's positioning, with an average fusion being applied to combine all predictions and estimate the patient-specific AoA plane.

Results

Data: To validate the proposed framework, thirty datasets from a publicly available CMR benchmark⁹ were gathered and processed. This database includes a heterogeneous population, with datasets with a variety of quality levels (from high quality to high noise ones). To establish a ground truth for the segmentation, an experienced observer (henceforth named Manual1) delineated the AV tract in 10 out of the 30 available volumes (the benchmark's training cases) by manually tracing 14 to 18 planes perpendicular to its axis, from which a 3D surface was obtained by interpolation as previously described.⁶ Moreover, for a clinical validation, annular area-derived diameters were assessed manually in all 30 cases. In each case, the AoA plane was identified by the observer by exploring the 3D CMR volume using three orthogonal planes, with the annulus being manually delineated to extract the measurement. To establish the interobserver variability, a second observer (henceforth named Manual2) repeated the manual tracing at the AoA plane identified by the first observer.

Segmentation performance: The performance of the AV tract segmentation algorithm was assessed by computing the absolute point-to-surface (P2S) distance between semi-automatically segmented surfaces and reference ones. Figure 2 summarizes the performance after each step of the segmentation framework. Possible variants of each step (e.g., initialization with a fixed tube instead of SSM-based initialization, or any of the two-stage evolution without SSM regularization terms) are also depicted. Overall, there is a significant reduction of the average error between all steps, with the inclusion of the profile-based SSM during initialization and segmentation providing further improvements. The proposed strategy obtained an average P2S distance error of 0.54 ± 0.08 mm in the 10 tested cases, taking around 1 sec to obtain the AV tract surface (excluding the time taken to identify the two user defined points). Figure 3 presents some example segmentation results, with associated P2S errors mapped on the AV tract surface. Finally, the influence of varying some of the algorithm's parameters was assessed, with the proposed framework demonstrating to be robust and stable within a fair range of parameter settings (data not shown due to page count limit).

Clinical measures evaluation: Figure 4 presents the Bland-Altman agreement between semi-automatic AoA measurements and manually extracted ones. The interobserver agreement is also reported. Overall, the proposed strategy showed an excellent agreement (-0.30 ± 0.77 mm), with its limits of agreement having no statistically significant difference to the ones seen between observers (in a two-tailed *F*-test).

New or breakthrough work to be presented

- (1) Aortic valve tract segmentation and sizing in 3D CMR images using shape-based BEAS and automatic aortic annulus detection.
- (2) Quantitative validation of the automated segmentation surface and aortic annulus measurements against manual-based assessment.

Figure 2 - Segmentation performance in the ten training datasets throughout the different steps of the segmentation framework, as well as possible variants of each step. * $p < 0.05$, two-tailed paired *t*-test; § $p < 0.05$, two-tailed *F*-test.

Figure 3 - Three segmentation examples, corresponding to the best (left), median (middle) and worst (right) results in terms of average P2S distance. To assess errors' spatial distribution, the surfaces are mapped with the absolute distance error. In the bottom row, the automated contours are shown in red, while manual ones are depicted in green.

Figure 4 - Bland-Altman analysis between automated and manual sizing strategies (A), and between two observers (B).

Conclusions

In summary, this study describes a semi-automatic framework for AV tract segmentation and sizing in 3D CMR images using the shape-based BEAS algorithm and an annulus plane detection strategy. The framework proved to be accurate, robust and computationally efficient in a publicly available benchmark, demonstrating its potential for accurate prosthesis sizing in preoperative TAVI planning.

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