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Chapter 5

Automated CTA Based Measurements for Planning Support of Minimally Invasive Aortic Valve Replacement Surgery

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5.1 Abstract

Minimally invasive aortic valve replacement (mini-AVR) procedures are a valuable alternative to conventional open heart surgery for patients with severe aortic valve stenosis. Currently, planning of the mini-AVR consists of selection of the intercostal space closest to the sinotubular junction on preoperative computer tomography images. We developed an automated algorithm detecting the sinotubular junction and intercostal spaces for finding the optimal incision location. In all 20 patients, the intercostal spaces were accurately detected. The accuracy of the sinotubular junction detection was assessed by comparison of its center location with manual delineation. This resulted in a mean paired distance of $3.4 \pm 2.4$ mm compared to the interobserver variation of $1.9 \pm 1.0$ mm. For 60% of patients, the fourth intercostal space was the closest to the sinotubular junction’s center. The proposed algorithm is the first automated approach for detecting optimal incision location and has the potential to be implemented in clinical practice for planning of various mini-AVR procedures.

Index Terms— CT angiography, Mini-AVR, Segmentation, Sinotubular junction, Intercostal spaces.
5.2 Introduction

Aortic valve stenosis is the most common valve disease in elderly. It has a strong age-associated prevalence of 0.2% in adults between 50-59 years old while this increases to 9.8% for the age of 80-89 [1,2]. The most common cause of aortic valve stenosis is senile calcific aortic valve disease, referring to a degenerative process associated with aging, causing lipid infiltration, inflammation and calcification of the valve leaflets[3,4]. Collagen fibers of the valve leaflets are destroyed, and calcium is deposited resulting in increased leaflet thickness and stiffness [5]. Aortic valve stenosis starts with mild to moderate leaflet changes, without symptoms and progresses to a severe symptomatic obstructing stenosis with high morbidity and mortality rates if left untreated [6]. Therefore, treatment is indicated in patients with severe symptomatic stenosis. Since there is no medical preventive therapy, aortic valve replacement (AVR) is inevitable.

During AVR, the aortic valve is replaced with prosthesis. The traditional AVR is performed during an open surgical procedure with full sternotomy with arterial cannulation in the ascendant aorta and venous cannulation in the right atrium in order to enable extracorporeal circulation by means of a heart-lung machine [7]. Full sternotomy has the advantage of a direct view of and access to all the cardiac structures [8]. Open surgical AVR is currently the most common valve replacement procedure in Europe and North America [9].

During the past decade, surgical techniques improved creating an area for less and minimal invasive procedures, a range of procedures classified as minimally invasive aortic valve replacement (mini-AVR) were introduced (Figure 5.1).

Figure 5.1 Schematic figure showing open heart surgery (Left) Mini-AVR (Right). Reprinted with permission [10].

Mini-AVR can be regarded as a conceptual approach of surgical techniques rather than one single approach. The broad range of mini-AVR procedures includes a spectrum of numerous approaches, described in different review studies, all with the aim of minimizing the degree of surgical intrusiveness [7,8,11,12].

Compared with conventional surgery, mini-AVR has shown to reduce postoperative mortality and morbidity including blood loss and postoperative pain. In addition, it is described that patients recover faster requiring less rehabilitations resources and
shorter admission time, which contributes further to reducing the risk of wound infection and consequently cost reduction [13–17].

The decision to select one of the mini-AVR techniques largely depends on the clinical characteristics of the patient and the experience of the operator and center [7,12]. The most commonly applied techniques are ministernotomy (MS) and right anterior minithoracotomy (RT) (Figure 5.2). MS is performed through a vertical incision through skin and sternum and completed by a transverse sternal incision [18], while RT is performed through a 5 to 6 cm skin incision at the level of the second or third intercostal space, starting from the border of the sternum toward the lateral right side [19].

**Figure 5.2: Schematic drawing showing intercostal spaces (A), minimally invasive aortic valve replacement techniques: Ministernotomy (B), and Right anterior minithoracotomy(C).**

For both techniques, the selection of the optimal location of the incision is one of the most important aspects of a successful valve replacement [20]. The optimal location is defined as the intercostal space (ICS) closest to the sinotubular junction (STJ) of the aortic root [21]. This closest ICS differs between patients for example due to prolonged aortas in the elderly. Choosing a suboptimal ICS may increase the complexity of the procedure, leading to longer operation time resulting in increased ischemic times, or conversion to full sternotomy [15,21,22]. Aortic valve sizing parameters such as aortic annulus radius and annulus to ostium distance are important as well for preoperative planning. In an earlier study, we proposed an automated method detecting aortic root landmarks and calculating these sizing parameters [23].

Preoperative planning of patients eligible for mini-AVR is done using computed tomography angiography (CTA) (Figure 5.3). Currently, the preoperative planning measures are performed manually, which makes them prone to interobserver variation. Therefore the usage of automated image based analysis could be of benefit to support and standardize the preoperative planning. A previous study proposed a visualization system for surgical planning of mini-AVR candidate patients using CTA images. The tool renders the chest cage with the ascending aorta and the final decision to continue with a mini-sternotomy or to convert to a full sternotomy is done by the surgeons based on their visual assessment [21,24].
However, to reduce error judgments an objective assessment and planning may enable optimal exposure, despite the mini-approach. Today, no studies describing a complete automatic planning measurements assessment for mini-AVR have been published.

According to the literature, non-contrast computed tomography is preferred to use for more clear evaluation of the chest cage [21,25,26], while CTA is used to evaluate insights in aortic stenosis in combination with the planning. Usage of CTA adds some difficulties for the automated extraction of bone structures because the contrast-enhanced blood vessel lumen has similar Hounsfield Units as bone [27,28]. Automatic detection of the ICSs on CTA images of patients eligible for mini AVR is also challenging. Because the patient population is relatively old, there is a great variation in shape, aspect topology, and size of the sternum. Moreover, patients may be suffering from deformations and disconnectivity of their sternal bones due to aging or previous surgeries [29]. However, we will show that CTA is feasible to sue for planning.

We introduce a fully automatic algorithm to detect the STJ and the bilateral second, third and fourth ICSs to determine the optimal incision location.

5.3 Methods

In this section, we present the proposed methods; starting by segmenting the aortic root, detecting the STJ, detecting the ICSs, and calculating the closest ICS to the STJ.

5.3.1 Data Collection

We retrospectively collected datasets of twenty consecutive patients in whom a 3D CTA was performed as part of the pre-operative planning for mini-AVR. For analysis,
we selected the volume at 70% of the cardiac cycle; the phase mimicking the non-beating heart connected to the cardiopulmonary bypass during surgery [30]. Image volumes contained 500–600 slices with 512 × 512 pixels and 16 bit depth. The in plane image resolution was isotropic and varying from 0.44 mm to 0.68 mm. The slice thickness for all data sets was set to 0.9 mm and an overlap of 0.45 mm.

### 5.3.2 Intercostal Space Detection

For the segmentation of bone, and heart tissue, we used double thresholding with an upper threshold of 1300 HU to exclude calcium and 1100 HU as a lower threshold. For each coronal slice, the number of bone voxels was determined. The most anterior local maximum of the number of bone voxels was selected as the coronal slice with the sternum. A Maximum Intensity Projection (MIP) image was created of the subvolume starting 10 mm anterior and ending 10 mm posterior to the sternum coronal plane. After an intensity-based thresholding, mathematical erosion is applied to remove connections of the sternum with the ribs. Subsequently, a morphological thinning is applied to determine the skeleton of the sternum (Figure 5.4).

![Figure 5.4: (A) Maximum intensity projection showing bone intensities, eroded sternum in red, and skeleton in black. (B) Sagittal view of the sternum with detected seed points; (C); the region growing result; (D) Coronal view of the sternum and the cartilages with cross section image on both sides with detected centroids in red and intercostal spaces in green.](image)

We propose to segment sternum bone marrow using 3D region growing, which requires a set of seed points inside the sternum. The anterior and posterior bones of the sternum are detected by locating the local intensity maxima anterior and posterior to the skeleton. Based on the first and second local maxima, an average point is calculated to be used as a seed point, located inside the sternum bone marrow. After removing outlying locations using median filtering, the remaining points were selected as seed points for the 3D region growing algorithm to segment the sternum bone marrow. Morphological dilation for the 3D segmented sternum bone marrow with 3D kernel sized 6 mm for the sternum bone marrow was applied to match the borders of the sternum bone.

The intersection of the two lateral sternum sides and the 3D CTA volume was calculated. k-means clustering was used to segment each rib cartilage cross section in the reconstructed image (Figure 5.4). The three dimensional location and intensity were used as features for the clustering. Centroids of the ribs and cartilages cross sections were extracted using k-means clustering from which the ICSs were estimated as the middle points between each two ribs’ centroids (Figure 5.4).
5.3.3 Sinotubular Junction Detection

The aortic root was segmented using a previously presented approach which uses supervised maximum likelihood classification and a 3D normalized graph cut [31]. Contours of the aortic root surface in MPR planes perpendicular to the centerline were analyzed. Three features were used to select the slice where one of these slices was considered a STJ (Figure 5.5).

![Figure 5.5: Schematic representation of the aortic root surface with the location of the sinotubular junction (Left). The two graphs on the right show the assembled features and its gradient (Right).](image)

Those three geometrical features for each slice lumen contour are the contour area, the second and third harmonics of the radial function in the frequency domain (Figure 5.6). These features were preferred since the contour area strongly decreases distal from the STJ compared to the area of the aortic root with its bulging cusps, the second harmonic emphasizes the elliptical radial function that is associated with the left ventricle out flow tract and ascending aorta, and the third harmonic is a good representative of the three cusps radial profile, so we expect strong contribution for the third harmonic in the region of the aortic root and a smaller contribution in the ascending aorta. The three geometrical features and the location of the STJ location are shown in Figure 5.6.
To select the slice corresponding to the STJ, we combined the three features by dividing the third harmonic by the second harmonic and multiplying it with the area. The resulting signal was convolved with the Laplace operator, generating two local maxima that correspond to the STJ and the aortic annulus. The local maximum most distal from the aortic sinuses was considered as the location of the STJ (Figure 5.7).

### 5.3.4 Intercostal Space to Sinotubular Junction Distance Measurements

The distance from the ICSs to the STJ was calculated for all ICSs and the minimum distance was presented as the preferred incision location for the delivery of the valve. For the right anterior minithoracotomy (RT), we only considered the right ICSs. For the ministernotomy (MS), we considered both right and left ICSs.
5.3.5 Validation

We validated the automatic detected STJ and ICSs to find optimal incision locations with manual assessments as a reference. The reference selections were generated by two trained radiologists by determining the STJ plane using 3mensio software [32]. The observers determined the reference locations manually and 3mensio was used for the manual annotations to provide an accurate visualization of the aortic root anatomy. The observers placed three landmarks defining the STJ.

The detection error of the automated method was evaluated by measuring the 3D Euclidean distance between the center of the automatically detected STJ and the center of the manual annotated points. ICSs were evaluated visually by giving each detected ICS a score of accurate, inaccurate, or reject. The number of patients proposed for each incision location was reported in case of right mini-sternotomy or for procedures for which both right and left incisions are allowed.

Statistical analysis was performed using MATLAB. Continuous variables; error of the automatic detection of the STJ points, and interobserver differences are reported as a mean, ± standard deviation, and median.

5.4 Results

The algorithm was evaluated using image data sets of twenty patients with severe aortic valve stenosis including six females and fourteen males with a mean age of 82 ranging between 68 and 93. Two patients have had cardiothoracic surgery in their medical history.

The sternum was successfully detected in all images. Visual inspection showed that the ICSs were accurately determined for all images except for one patient with an inaccurate detection. In Figure 5.8, the detected ICSs are shown on a maximum intensity projection image of the sternum.

![Figure 5.8: Three examples of the sternum MIP images with the six detected intercostal spaces depicted with a red point.](image)

The STJ was successfully detected in all twenty patients. The accuracy of the STJ center detection is shown in Table 5.1. The mean distance between centers of the automatically detected landmarks and the manual reference points was 3.4 ± 2.4 mm.
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The mean distance between the manually determined STJ centers was $1.9 \pm 1.0$ mm. The average distance between ICSs and the center of the STJ is calculated. The distances between both right and left ICSs to the STJ center are described in Table 5.2.

For nine patients, the left fourth ICS was closest positioned to the STJs, where the second most frequent location closest to the STJ was the left third ICS for five patients. For solely right sided incisions, the closest ICS are shown in Table 5.3.

Table 5.1: Accuracy of sinotubular junction center detection for the proposed technique and the interobserver variation.

<table>
<thead>
<tr>
<th>Sinotubular Junction Detection</th>
<th>Mean ± STD (mm)</th>
<th>Median (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed Algorithm</td>
<td>3.4 ± 2.4</td>
<td>2.6</td>
</tr>
<tr>
<td>Interobserver Variation</td>
<td>1.9 ± 1.0</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 5.2: Average distance of each intercostal space and the sinotubular junction center for all patients.

<table>
<thead>
<tr>
<th>Mean Distance to the Sinotubular Junction Center</th>
<th>Right Intercostal Space Mean ± STD (mm)</th>
<th>Left Intercostal Space Mean ± STD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second Intercostal Space</td>
<td>83.1 ± 14.7</td>
<td>80.1 ± 13.7</td>
</tr>
<tr>
<td>Third Intercostal Space</td>
<td>73.6 ± 12.3</td>
<td>70.7 ± 11.9</td>
</tr>
<tr>
<td>Forth Intercostal Space</td>
<td>73.4 ± 11.6</td>
<td>69.9 ± 10.9</td>
</tr>
</tbody>
</table>

Table 5.3: Frequency; number of patients; of the closest intercostal space to the sinotubular junction for both approaches (ministernotomy and right anterior minithoracotomy). First two columns present frequencies for ministernotomy intercostal spaces and third column presents frequencies for right anterior minithoracotomy intercostal spaces. ICS: Intercostal Space.

<table>
<thead>
<tr>
<th>Number of Patients</th>
<th>Ministernotomy</th>
<th>Right Anterior Minithoracotomy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right ICS</td>
<td>Left ICS</td>
</tr>
<tr>
<td>Second ICS</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Third ICS</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Forth ICS</td>
<td>2</td>
<td>9</td>
</tr>
</tbody>
</table>

In twelve patients, the fourth ICS was found to be the closest incision point to the STJ for, in six patients, this was the third ICS and only two patients were found to have the second ICS close to the STJ. In Figure 5.9, an interpolated distance map is presented, showing the distance of the center of the STJ to the ICSs.
5.5 Discussion

We presented an algorithm that automatically determines the distance between intercostal spaces and the sinotubular junction to support optimal incision location selection for mini AVR procedures. The proposed algorithm showed good accuracy for STJ detection. Visual inspection of the detected ICSs also showed a high accuracy for all but one patient.

By our tool, the ICS selection for valve delivery was made based on measuring which ICS is closest to the center of the STJ. The fourth ICS was found to be the closest one to the STJ’s center in 60 and 55% when considering both sides of the sternum for MS and for RT considering only right side ICSs for delivering the surgery, respectively.

Cardiothoracic surgeons most often choose the third ICS by default [33]. In our patients, there was only a small difference between the STJ-third-ICS distance and STJ-fourth-ICS distance. However based on the shortest distance measurements, the number of patients with an optimal incision location at the fourth ICS is two times higher than the number of patient with the third ICS as an optimal incision location. In current literature the second ICS has not been reported for the incision position. Surprisingly, with the automatic planning, we found that the second ICS was the closest in 10 percent of the patients when selected for right anterior minithoracotomy.

To make sure that our measurements are accurately representing the position, orientation of the heart during the surgery where the heart is cannulated and connected to a cardiopulmonary bypass machine, we used the CTA images acquired at 70% of the cardiac cycle representing the end diastole of the heart. However, slight differences in the orientation and position of the heart between scanning and surgery can be expected.
Schechter et al [34], evaluated heart movement during the respiratory cycle and it was found that during inspiration the heart moved caudally with a mean displacement of 4.9 ± 1.9 mm and anteriorly with mean 1.3 ± 1.8 mm during inspiration. This caudal displacement could slightly influence the accuracy of our measurements. Also, the automated analysis suffered from incomplete volume of interest in one patient image dataset which led to inaccurate detection of ICSs.

We chose to segment the bone marrow of the sternum instead of the sternum bone itself for multiple reasons. First of all, automated analysis methods are hampered by the similar intensity values of contrast-enhanced blood and bone which, increases the difficulty of sternum bone and blood vessels separation. Also, most patients with aortic valve stenosis are elderly and therefore have bone degeneration and lower bone densities compared to young patients [35,36]. In addition, we found in our patient population with a history of cardiothoracic surgery that strong and blooming sternal wires and incomplete sternum connectivity on CTA images. In the five patients with a sternal foramen, region growing to segment the sternum bone was inaccurate.

The proposed algorithm is the first 3D based planning tool for mini-AVR. We introduced a standardized way to select the optimal incision location. This could reduce in site complications caused by the selection of the suboptimal ICS such as extension to costal cartilage incision (median sternotomy) or full sternotomy to deliver the aortic valve. The proposed solution may support clinical decision making by current experienced surgeons. The automated calculation for planning should make the preparation easier and more efficient for the operator, further the accuracy and safety should be optimized. However, the automated algorithm should not replace the manual images inspection in general.

Moreover, standardizing of the planning will introduce a guideline for new trainees to improve learning this procedure and will be used as an assisting tool, where it gives a 3D imagination/mimicking of the access. It could help in reducing the training time of the new trainee doing the AVRs in the wetlab (e.g. pig hearts were used for acquiring procedural skills, not for mimicking access). Also, it may reduce conversion rate to full sternotomy and help trainee.

Incision location is an important parameter in the planning of various minimally invasive cardiothoracic surgeries. We believe that our solution may help surgeons by adding extra measurements or some customizations to fit each surgery requirements. As an example, minimally invasive mitral valve repair mini-MVR, minimally invasive right coronary artery bypass grafting mini-CABG, and minimally invasive direct coronary artery bypass MIDCAB which use right anterior minithoracotomy [37], right ministernotomy [38], left lateral thoracotomy [39] surgical approaches respectively. The position of the ascending aorta related to the sternum location is important measure for transaortic transcatheter aortic valve implantation to select either the right minithoracotomy or left ministernotomy for delivering the prosthetic [40]. Further the chosen surgical approach is could also vary for patients and centers, specifically the access via lateral thoracotomy, which is performed by only a few centers.
Image data from one single medical center and scanner was used in this study. Although there was a large variety in scanned volumes, image to noise ratio, and anatomy, different scanning protocols may require adjustments of the presented algorithm. Only twenty patient data were included to determine the detection accuracy. However, this was sufficient to demonstrate the potential of automated CT based measurements for finding the closest access. The low number of observers who contributed to our manual annotation can be considered a limitation of the study. Furthermore, the impact of the ICS selection has not been validated with surgery outcomes. Clinical validation will be needed for that prospective application.

5.6 Conclusion

We introduced an automated method determining the closest ICS to the STJ as the optimal incision location for mini-AVR procedures on preprocedural CTA. This is the first automatic algorithm to be developed for preoperative planning of cardiothoracic surgery. The algorithm was evaluated by comparison with expert delineation and showed good accuracy. This work has the potential to be implemented in clinical practice for supporting mini-AVR planning.

Informed Consent The Institutional Review Board granted approval of the study design and waived informed consent since solely data obtained in the context of clinical care is utilized.
5.7 References


Automated CTA based Measurements for mini-AVR Support


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