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Automated CTA based measurements for planning support of minimally invasive aortic valve replacement surgery

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ABSTRACT

Minimally invasive aortic valve replacement (mini-AVR) procedures are a valuable alternative to conventional open heart surgery. Currently, planning of 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 (STJ) and intercostal spaces for finding the optimal incision location. The accuracy of the STJ detection was assessed by comparison with manual delineation by measuring the Euclidean distance between the manually and automatically detected points. In all 20 patients, the intercostal spaces were accurately detected. The median distance between automated and manually detected STJ locations was 1.4 [IQR = 0.91–4.7] mm compared to the interobserver variation of 1.0 [IQR = 0.54–1.3] mm. For 60% of patients, the fourth intercostal space was the closest to the STJ. 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.

1. 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 and 59 years old which increases to 9.8% for the age of 80–89 [1]. 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 [2].

During Aortic Valve Replacement (AVR), the aortic valve is replaced by a prosthesis. Traditional AVR is performed during an open surgical procedure with full sternotomy and with arterial cannulation in the ascendant aorta and venous cannulation in the right atrium to enable extracorporeal circulation by means of a heart-lung machine [3]. Full sternotomy has the advantage of a direct view of and access to all the cardiac structures [4]. Open surgical AVR is currently the most common valve replacement procedure [5].

During the past decade, surgical techniques improved creating an area for less and minimal invasive procedures. Also a range of procedures classified as minimally invasive aortic valve replacement (mini-AVR) was introduced (Fig. 1). Mini-AVR can be regarded as a conceptual approach of surgical techniques rather than one single approach. Compared with conventional surgery, mini-AVR has less bleeding and has shown similar postoperative mortality and morbidity rates. In addition, patients recover faster requiring less rehabilitations resources and shorter admission time [6,7].

The most commonly applied techniques are ministernotomy (MS) and right anterior minithoracotomy (RT) (Fig. 1). MS is performed through a vertical incision through skin and sternum and completed by a transverse sternal incision [8], while RT is performed through a 5–6 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 [9].

For both techniques, the selection of the optimal location of the incision is one of the most important aspects of a successful valve replacement [10]. The optimal location is defined as the intercostal space (ICS) closest to the sinotubular junction (STJ) of the aortic root [11]. This closest ICS differs between patients, for example due

Abbreviations: AVR, Aortic Valve Replacement; Mini-AVR, Minimally invasive Aortic Valve Replacement; MS, Ministernotomy; RT, Right Anterior Minithoracotomy; STJ, Sinotubular Junction; ICS, Intercostal Space; CTA, Computed Tomography Angiography; MPR, Multi Planar Reformat; MIP, Maximum Intensity Projection; HU, Hounsfield Units; ICC, Intraclass Correlation Coefficient.

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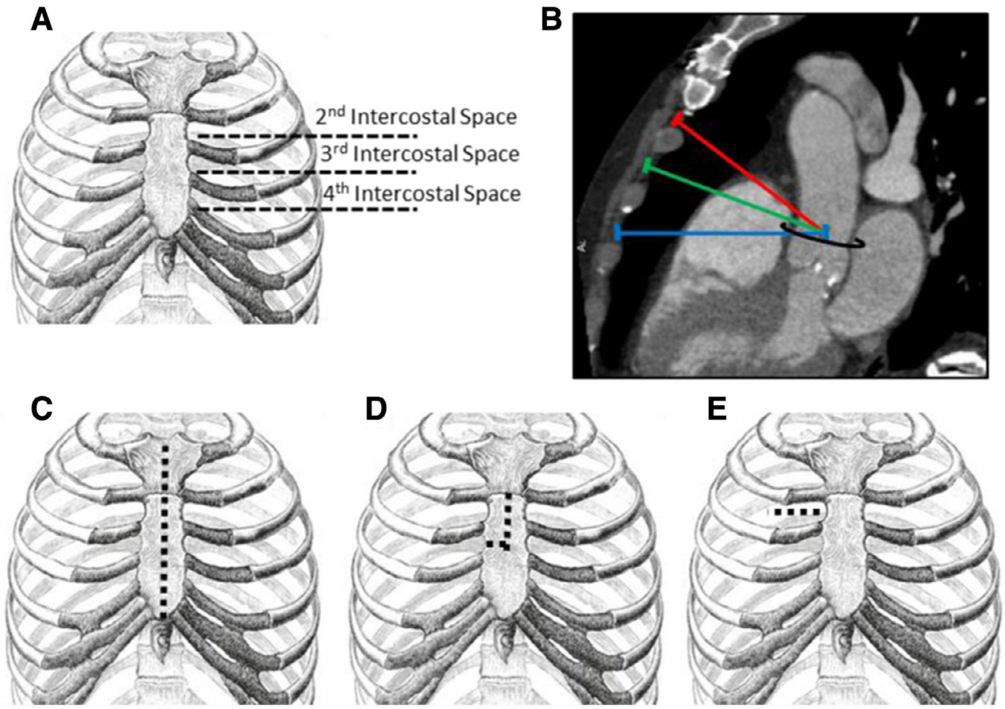

Fig. 1. Schematic drawing showing intercostal spaces (A), Multi-planar reformatted plane showing intercostal spaces and the ascending aorta and the three colored lines represent the distances for three intercostal spaces to the sinotubular junction (B), open heart surgery (full sternotomy) (C), minimally invasive aortic valve replacement techniques: ministernotomy (D), and right anterior minithoracotomy (E).

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 [11,12]. 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 [13].

Preoperative planning of patients eligible for mini-AVR is done using computed tomography angiography (CTA) (Fig. 1). 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 for the type of procedure is based on visual assessment [11,14]. The manual assessment is prone to interobserver variation. Automated and quantified image based analysis could be of benefit to support and standardize the preoperative planning. Up to date, no studies describing a complete automatic planning measurements assessment for mini-AVR have been published.

Automatic detection of the ICSs on CTA of patients eligible for mini-AVR is challenging. Because the patient population is relatively old, there is a great variation in shape, topology, and size of the sternum. Moreover, patients may be suffering from deformations and disconnectivity of sternal bones due to aging or previous surgeries [15].

In this study, we introduce and validate a fully automatic algorithm to detect the STJ and the ICSs to determine the optimal incision location as a proof of concept of a mini-AVR planning tool.

2. Methods

We here present the proposed methods starting with segmenting the aortic root, detecting the STJ, detecting the ICSs, and determining the closest ICS to the STJ. All methods introduced in this work were developed using MATLAB (R2014a, The Mathworks Inc., Natick, MA).

2.1. Data collection

We retrospectively collected datasets of twenty consecutive patients in whom a 3D CTA was performed as part of the preoperative planning of AVR. For analysis, we selected the late-diastole phase volume, because at this cardiac phase the heart resembles the arrested heart during the extracorporeal circulation step best [16]. All CT-scans were performed on a Philips Brilliance 64 slice CT scanner. The chest, abdomen and pelvis were scanned using one bolus of 120 ml contrast Iomeron 400, intravenously infused at a rate of 5 ml/s. 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 0.9 mm with an overlap of 0.45 mm.

2.2. 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 according to reported average bone densities in old patients [17]. 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. Mathematical erosion with a structure element sized $9 \times 9 \times 9$ mm was applied to remove connections of the sternum with the ribs. Subsequently, a morphological thinning was applied to determine the skeleton of the sternum (Fig. 2).

We 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