A New Method for Intraoperative Quantification of Mitral Leaflet Segment Prolapse

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Abstract

During mitral valve reconstruction, intraoperative valve analysis is carried out by the cardiac surgeon for assessing location and extent of leaflet defects. The analysis of each leaflet segment is usually examined using two nerve hooks, as proposed by Carpentier. Qualitative comparison between the possible displacement of the segments is done in order to evaluate motion restriction or prolapse. However, this comparison depends on the subjective assessment and the experience of the surgeon. We propose a new computer-based approach which allows for a quantitative measurement of the segment displacement in relation to the annulus plane. Infrared reflecting markers are attached to the instruments for optical tracking. The segments are examined as proposed in the Carpentier method using either a single or two nerve hooks. Evaluation was carried out by repeating measurements three times on an excised porcine heart. Mean chordae were cut to induce a prolapse iatrogenically. The single-hook procedure turned out to be less time-consuming and easier to perform and showed a high reproducibility (mean standard deviation: 1.51 mm) in comparison to the hook-pair approach (3.35mm). Our method overcomes the limitations of actual subjective analysis, enables to get quantitative and highly reproducible measurements of leaflet prolapse and may provide valuable decision support during surgery.

1. Introduction

The mitral valve, also known as the bicuspid valve or left atrioventricular valve, consists of two leaflets: the anterior and posterior leaflet. As proposed by Carpentier [1] and widely used, the posterior leaflet of the mitral valve is divided into three segments according to its scallops: They are referred to as P1 (anterolateral), P2 (middle), and P3 (posteromedial). The corresponding segments of the anterior leaflet are labeled A1, A2, and A3 (cp. with figure 5).

Mitral valve prolapse is defined as displacement of the free edge of the leaflet superior into the left atrium above the mitral annular plane [2]. In severe cases, this has to be repaired in a setting of a surgical intervention. The findings on the grade of the prolapse and its cause influence the surgical procedures during the intervention, such as leaflet resection or chordae plasty.

Transesophageal echocardiography (TEE) ultrasound data is the standard imaging method for mitral valve analysis. TEE is used for grading mitral valve insufficiency including localization and extent of the leaflet prolapse, e.g., it is of interest whether the prolapse is restricted to a single segment or stretches over neighboring segments. This fact substantially influences the complexity of the mitral valve repair and therefore requires profound expertise of the surgeon. Biaggi et al. [3] found out that real-time three-dimensional (3D) TEE is more accurate than two-dimensional (2D) TEE in identifying prolapse of single segments and in patients with advanced valve prolapse. However, ultrasound suffers from a lack of resolution and is prone to artifacts.

The gold standard for defining mitral valve pathology remains intraoperative measurement by a reference surgeon [3] in order to confirm or modify the preoperative ultrasound findings. Only very few studies have tested the accuracy of 3D TEE in quantifying mitral valve anatomy compared with direct surgical measurements. Biaggi et al. [3] used a caliper, a long Kelly clamp or a ruler in case of suboptimal exposure for intraoperative measurements, while [4, 5] used a flexible metric ruler.

In a normal clinical setting, qualitative judgement of the valve morphology remains the state-of-the-art technique. The motion and tissue pliability of the leaflets are usually examined with a two nerve hook method as proposed by Carpentier [1]. The first nerve hook is placed at the free edge of a reference leaflet segment, which is typically the P1 segment. P1 is assumed to be rarely affected by abnormal leaflet motion compared to other leaflet segments and thus should not override the plane of the annulus when pulling it upwards. The second hook is placed consecutively at one of the free edges of the remaining segments (A1-A3, P2-P3). Traction perpedicular to the annulus plane is exerted by the surgeon on both nerve hooks. Qualitative comparison between the displacement of the segments is done by the surgeon in order to evaluate motion restriction or prolapsing segments.

The drawback concerning this approach is that it is an user-dependent analysis based on the experience of the surgeon hampered by a restricted field of view. The surgical view is from the atrium towards the valve (top view). Distances that lie along the view direction of the surgeon, such as the displacement between the two hooks when pulling at the free leaflet edges, are hard to predict visually. Thus, the variability among different experts concerning a qualitative examination and judgement of the leaflet displacement might be high.

Our ultimate goal for segment analysis was to find a fast, precise and user-independent procedure, which allows for a straightforward integration into the current surgical workflow with minor efforts. In this work, we propose a new computer-based approach which allows for a quantitative measurement of the segment displacement in relation to the annulus plane. This is done by incorporating optical tracking into the state-of-the-art procedure, while making minor extensions to the routine. We have already shown that the intraoperative geometry of the valve can be determined by pinpointing to specific landmarks using pointing instruments that are optically tracked within less than two minutes [6].

Figure 1. Prototyps of tracked instruments with hooks, rounded and straight tips. In the case of the hooks, the position of the inner angle is calibrated (black arrow), the tip otherwise.

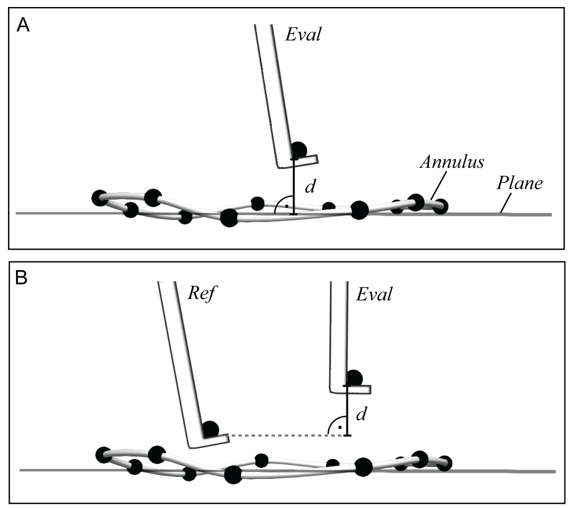

Figure 2. A) Segment analysis with a single hook. The distance d between inner hook angle and plane is measured. B) Procedure performed with a hook pair. d is the distance between both hooks along the plane normal.

2. Methods

We propose a new computer-based approach of the Carpentier method [1] which allows for quantitative measurement of the segment displacements when exerting force on it.

Different instrument prototyps were designed (hooks, pointer with straight or with rounded tips) and equipped with spherical markers which reflect infrared light (figure 1). A stereoscopic optical sensor (NDI Polaris, Canada) has been used for exact determination of the instrument's position. The position of the tip relative to the markers has been predetermined during instrument calibration. A software plugin for leaflet analysis has been written for the open source software toolkit Medical Imaging Interaction Toolkit (MITK) [7], which already provides an interface for embedding optical tracking [8]. A screenshot is presented in figure 5.

In the first step of our segment analysis procedure, the morphology of the annulus needs to be measured. One of the pointing devices is used to measure a various number of points (> 5) on the annulus in a clockwise manner starting at the proximity of the anterolateral commissure. Then, a plane (termed *annulus plane*) is fitted into these points using an orthogonal distance regression method, which minimizes the sum of squared distances of the measured points to the plane. The normal of the plane is oriented in the direction to the atrium.

Then, as in Carpentier's approach, the surgeon exert traction with two nerve hooks on the leaflet segments' free edges, using a predetermined segment as reference segment (see figure 2B). The nerve hooks are called *reference hook* and *evaluation hook* in the following. The 3D world

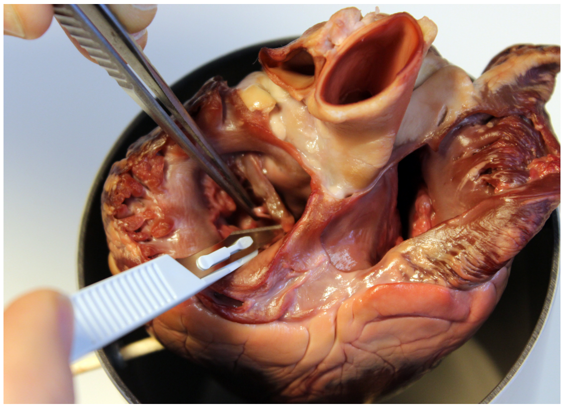

Figure 3. Fixated porcine heart, where the mean chordae at mitral leaflet segment A2 are cut.

position of the inner angle of the hook pair are determined by the software. Finally, the distance d along the annulus plane normal between the acquired position from the reference hook and the position from the evaluation hook is computed. The same procedure can be carried out employing only the evaluation hook (see figure 2A). In this case, the distance d between annulus plane and hook position along the normal of the annulus plane is evaluated.

During the measurements, the surgeon gets visual feedback on a screen, which displays of all measured points relatively to each other, to the annulus and to the current position of the tracked instruments. Virtual surface models represent the original instruments and their position and orientation are constantly updated (see figure 5). The measured points are rendered as spheres and color-coded connection are drawn between them. The color coding corresponds to a heat-map: line segments that are below the plane are rendered in blue while line segments above the plane are displayed in red. The actual distances are plotted in a table on the graphical interface next to the virtual scene.

3. Experiments and Results

We asked a cardiac surgeon to repeat measurements with one and two nerve hooks (as shown in figure 2A+B) three times in order to evaluate the reproducibility of the method. Evaluation was carried out on an excised porcine heart. The heart was fixated in a tube with wooden sticks. The left atrium was removed to expose the mitral valve. For a second experiment, the mean chordae tendineae at the leaflet segment A2 were cut to induce a prolapse iatrogenically (see figure 3).

The signed distances of the first experiment are plotted in figure 4. Values for leaflet displacement of opposite segments (A1-P1, A2-P2, A3-P3) have a larger deviation (1-5mm) among one another.

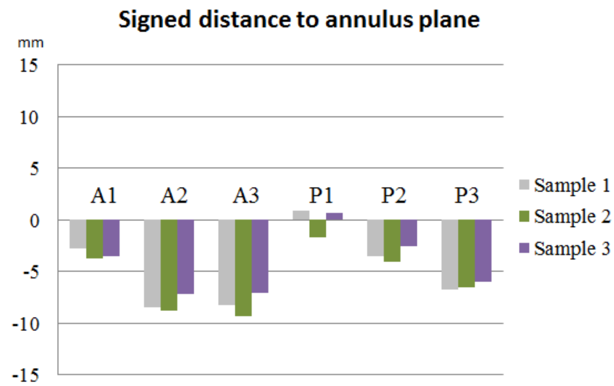

Figure 4. Diagram shows the signed distance to the annulus plane for three repeating measurements with a single hook on the unaltered valve (negative values for points measured below the annulus plane).

The single-nerve-hook procedure has proven less time consuming and easy performable and showed a high reproducibility of the measured distances (mean standard deviation: 1.51 mm $\pm$ 1.54 mm) in comparison to the two-nerve-hook approach (3.35mm $\pm$ 2.05 mm).

4. Discussion and Conclusion

Based on the results for reproducibility, we conclude that the handling and the control of hook (on instruments where additional rigid bodys are attached to) is more difficult for the user. Also, we observed line-of-sight problems between instruments and sensor when two hooks on a relatively small space had to be used, since one instrument occluded the spherical markers of the other one in some cases. This is a general problem optical tracking systems have to deal with, leading to a loss of tracking information during occlusions. However, the reproducibility of the measured displacements with a single nerve hook showed satisfying results in less time.

The experiments revealed that the morphology of the valve we examined may not correspond to the morphology we expect to see in a human heart. The distribution of the values in figure 4 shows that a plane fitted through the points of the free leaflet ends, when pulling with a hook is tilted along the septolateral axis as well as the commissural axis. Thus, the plane through the free leaflet ends is abnormally tilted. This was also confirmed by the surgeon by visual inspections on the porcine heart. In a human valve, we expected to see a plane that has approximately the same orientation as the annulus plane. We therefore conclude that the position of the measured points in relation to this annulus plane allows for a quantitative statement concerning the leaflets.

Figure 6 shows a result measured with a single nerve

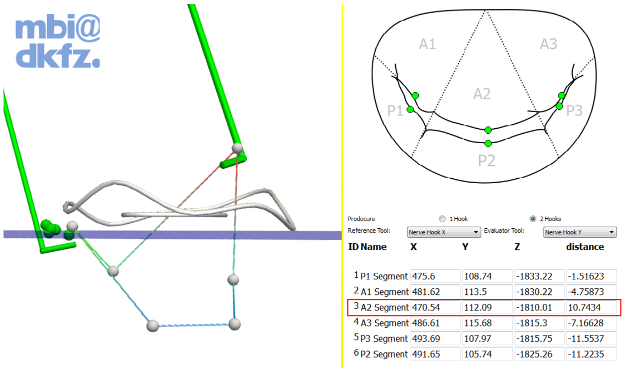

Figure 5. Screenshot of the MITK plugin together with a virtual scene during the measurements. The green spheres represent the reference points acquired by the reference hook (P1 segment). The annulus plane is translated to the current reference point. The white spheres indicate the positions after displacement of the free leaflet edges of the other segments.

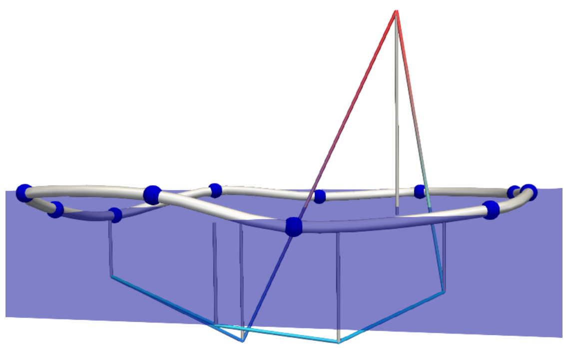

Figure 6. Color coded connections between the points facilitate better depth perception. Perpendicular connections between plane and points are shown additionally.

hook. The color-coded connections between the measured points facilitate an impression of their position in relation to each other and to the annulus independent of the view angle of the camera in the virtual scene.

All in all, our method overcomes the limitations of actual subjective analysis, shows a unique ability to get quantitative and highly reproducible measurements of leaflet prolapse and provides valuable decision support in terms of leaflet resection or chordae plasty. Future work includes the intraoperative application of the proposed method on a larger collective of patients suffering from mitral valve insufficiency. Furthermore, comparisons of our segment analysis method with distance measurements on preoperative TEE-ultrasound images are planned.

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