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Towards a New Image Guidance System for Assisting Transapical Minimally Invasive Aortic Valve Implantation

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Abstract—**We propose a new image guidance system for assisting transapical minimally invasive aortic valve implantation. The goal is to define the exact positioning of aortic valve prosthesis, preventing the misplacement of the valve. The proposed system consists of two stand-alone modules. First, preoperative planning software uses DynaCT images with manual anatomical landmarks to calculate the size and optimal position of the prosthesis. Second, an intraoperative system is developed for tracking of the prosthesis and the coronary ostia in 2-D fluoroscopic images. Then the safe area of implantation is defined. The preliminary experimental results of preoperative planning and intraoperative tracking system are promising.**

I. Introduction

Minimally invasive techniques have been applied in heart valve surgery since the mid 1990s [1]. Compared with standard surgical techniques, minimally invasive surgery has the benefits to cause minimal tissue, skin, and muscle damages. Moreover, the recovery time is reduced and the patient can return to normal activity more quickly.

Image guidance is important for minimally invasive procedures, because the interventionalist can not directly observe the anatomical or pathological target [2]. Medical imaging technology, including CT, X-ray fluoroscopy, MRI, and Ultrasound, is used to provide accurate information on the target area during preoperative planning and intra-operative procedures.

Transapical Aortic Valve Implantation (TA-AVI) is a new minimally invasive treatment of aortic stenosis for high risk patients [3]. It has been applied in more than 1000 cases in selected medical centers and presents a good alternative to standard aortic valve replacement.

The TA-AVI is performed on the beating heart without the need for sternotomy or cardiopulmonary bypass [3]. Through a left lateral mini-thoracotomy and the apex of left ventricle, a stented valve bioprosthesis is inserted into the aortic root using a catheter. After reaching the correct position, the stented prosthesis is deployed by an inflatable balloon to reach its final diameter, thus fixing the prosthesis to the aortic wall as shown in Fig.1 [3].

Once deployed, the prosthesis can not be repositioned. If the aortic valve prosthesis (AVP) is placed too high, the coronary arteries may be blocked, resulting in an emergency sternotomy. If the AVP is placed too low, the mitral valve leaflets might be damaged by the stent. The correct placement of the prosthesis is therefore crucial

Before implantation of the valve, the pre-surgical plan assesses the suitability of this surgical technique [2]. The preoperative data is necessary to understand the patient's aortic root anatomy and the aortic valve stenosis, measure the optimal size of the prosthesis, and find the optimal position for implantation. For TA-AVI, CT images are used for accomplishing preoperative planning.

During the intervention, the placement of the AVP is done under 2-D X-ray fluoroscopy guidance. Contrast agent is injected to visualize the aortic root with the coronary ostia.

Until now, TA-AVI relies mainly on the subjective assessment and the professional experience of the surgeon. It is likely that an image guidance system for assisting TA-AVI would lead to higher precision in TA-AVI by defining automatically the safe area of implantation, reduce the surgery time for controlling the position of AVP, and safer operation with less risk for the patient.

The motivation of this work is to develop a new image guidance system in order to improve the implantation accuracy of AVP in preoperative planning and intra-operative procedures of the TA-AVI.

This paper is organized as follows. In Section II, we give an overview of the image guidance system including the preoperative planning software and intraoperative tracking system. The preliminary results of the proposed image guidance system are presented in Section III. Finally, conclusion and future work are included in Section IV.

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II. METHODS

Fig. 2 presents the block diagram of our proposed image guidance system for TA-AVI. Currently, the preoperative planning software and intraoperative tracking system are stand-alone modules with their own visualization and user interaction.

A. Preoperative Planning Software

The transcatheter valves used in TA-AVI are available in two sizes with respect to their diameter and length [4]. Implantation of a wrong sized valve has a negative effect on the outcome of the intervention [5].

We have developed preoperative planning software to measure the required size of the implant and to determine its optimal position [6]. The developed software is able to import 3-D images directly from the Siemens DynaCT imaging device or from a PACS.

In a semiautomatic process, a surface segmentation of the aortic root is created using a threshold-based region growing approach. The user sets a seed point into the aorta with the mouse and adjusts the threshold using a slider. The result of the region growing segmentation is passed to the marching cubes algorithm for 3-D surface generation [7].

Based on the anatomy of the aortic root, the user selects generic landmarks by clicking on the reconstructed surface segmentation. The anatomical landmarks are three points on the hinges of the leaflets that mark the ventriculoarterial junction, the coronary ostia, and the basal attachments of the leaflets which are the lowest points of the hinges.

Once the user accepts the landmark positions, the geometric constraints for the size and position of the prosthesis onto the aortic root are automatically calculated.

A DICOM prosthesis database following the proposed DICOM supplement 131 is queried for appropriate AVP templates and the optimal prosthesis is selected. Planning landmarks on the template are used to align it with the patient data.

After planning, all generated information is sent to a PACS server using DICOM syntax. From the PACS server, intraoperative systems, reporting tools, or simulation systems can retrieve the planning information for further processing.

B. Intraoperative Tracking System

Tracking the target such as the AVP, the coronary ostia in the fluoroscopic images is a challenging process [8]-[9], because the image contrast is generally low. Moving anatomical structures, catheters and guide wires may overlap the prosthesis which moves very fast due to the blood flow. Moreover the presence of contrast agent may hide the upper part of prosthesis. The coronary ostia are only shortly visible when the contrast agent is injected.

Our previously published work [10] for tracking of the AVP in 2-D fluoroscopic images has been modified and extended to include the tracking of coronary ostia in the images with/without the contrast agent. In consequence, the safe area of implantation can be defined.

1) *AVP Tracking:* We assumed that the AVP is a rigid object during the tracking process until the inflation of balloon to the prosthesis's final diameter. The proposed method of AVP localization and tracking includes two major steps: an initialization step, followed by the AVP tracking procedure. The initialization step includes generation of a model of the prosthesis based on a manually defined quadrangle of the AVP edges in the first image of sequence. Then a target window image around the AVP edges is automatically generated, in order to estimate the position of the prosthesis in the next fluoroscopic images using template matching technique.

To reduce the processing time and increase the robustness of the algorithm, a region of interest (ROI) is defined. It represents the area of the image where the AVP is expected to move within. In practice, the size of the ROI is selected 2.5 times the size of the target window and is constant for all the sequence.

After initialization, the AVP tracking procedure is started. It works fully automatic and performs as: the input fluoroscopic images are preprocessed using a morphological reconstruction and an adaptive Wiener filter, in order to reduce the image noise and adjust intensities within the sequence while preserving the important image features. Using template matching algorithm, the target window including the prosthesis image is detected to define the position of AVP in each image of the sequence. Then the four corner points of the AVP can be extracted based on the proposed AVP model within the target window. Finally, the AVP model is displayed to fit the prosthesis edges in the fluoroscopic images.

2) *Coronary Ostia Tracking:* Locating the coronary ostia during TA-AVI is a difficult task, because the aortic root is not visible in the fluoroscopic image unless the contrast agent is injected.

We assumed that the movement of the tracked prosthesis may be used to determine the motion of the aortic root as similarly proposed in [11]-[12]. Therefore, the coronary ostia can be also tracked even without the contrast agent.

The proposed tracking algorithm automatically detects the images in which the aortic root and the coronary arteries are filled with contrast agent using histogram-based feature of the images [13]. The image sequence is frozen as soon as the contrast agent is detected in this image to provide the manual initialization of coronary ostia locations. In the following, the motion of the AVP is used to extrapolate the motion of the coronary ostia.

The above assumption is still under development which is considered one of our proposed solutions to provide the ostia tracking without contrast agent in 2-D fluoroscopic images during the valve implantation procedure.

3) *Safe Area of Implantation*: We aim in this paper at implanting one-third to one-half of the prosthesis above the mid-level of the aortic annulus, avoiding the obstruction of coronary ostia [3]. Based on the qualitative information of

the preoperative planning step, the tracked prosthesis, and the coronary ostia, the safe area of implantation is automatically defined and tracked.

III. Results

Our image guidance system was evaluated using 16 DynaCT image sets and 6 fluoroscopic image sequences with a sequence length 40 frames from clinical routine of the TA-AVI for preoperative planning software and intraoperative tracking system respectively. All the tested images were acquired using Siemens Axiom Artis dTA® system at the Heart Center Leipzig, Germany.

A. Preoperative Planning Software

Fig. 3 shows a screenshot of the preoperative planning software. DynaCT images provide sufficient contrast for segmentation and localization of the anatomical landmarks for prosthesis template selection and registration.

Image processing takes about one minute. The user-interaction is required for accurate landmark placement which depends on the image quality and varies between two and ten minutes.

A prosthesis template database for the AVP was created in DICOM format and integrated into the PACS system which is accessible from the operating room (OR).

In some cases, the experiments show that exact determination of the landmarks is difficult due to artifacts or low contrast. However, the developed software is still capable of determining the geometric situation of the aortic root in a way that is sufficient for the AVP selection and implantation planning.

B. Intraoperative Tracking System

Fig. 4 shows the results of the intraoperative tracking system. The AVP, the coronary ostia, and the safe area of implantation are successfully tracked in all tested image sequences.

The tracking algorithm has been implemented using MATLAB®. Total processing time of the tracking algorithm is relatively slow approximately 1.3 seconds per frame.

The user-interaction is required to initialize the algorithm of tracking and to define the initial locations of the coronary ostia during the processing of image sequence.

Although the contrast agent is successfully detected in all six image sequences, the initial positions of the coronary ostia were difficult to place in two sequences because of low contrast in the detected images.

The localization distance errors of AVP and coronary ostia tracking in the tested sequences are determined by measuring the distance error between the automatic localization and the manual localization [14]. For the coronary ostia, the distance errors are measured only in the images with the contrast agent. The distance errors of localization in all fluoroscopic sequences are small ($d_{max} \leq$ 1.6 mm for the AVP and $d_{max} \leq$ 1.92 mm for the coronary ostia).

Based on the professional experience of the operating surgeon, we assumed that the maximum allowed error of the misplaced valve will be between 2 and 5 mm for this new surgical technique. The tracking results of the misplaced valve are therefore within the clinically acceptable range.

The above results of our developed preoperative planning software and intraoperative tracking system of the TA-AVI are promising. We are now going to validate this image guidance system for TA-AVI in the operating theatre.

IV. Conclusion and Future Work

We have presented our proposed image guidance system for assisting TA-AVI during preoperative planning and intraoperative valve placement. The preoperative planning software and intraoperative tracking system are still under development to further improve the placement of the prosthesis. We are working on speed up the processing time of the proposed tracking algorithm by re-implementing and optimizing the code using C/C++ programming language and hardware solutions; first test indicate a speed of application 20 fps.

The accuracy of valve implantation is expected to increase by overlaying the results of the preoperative planning software on 2-D fluoroscopic image sequences during the intraoperation of the TA-AVI.

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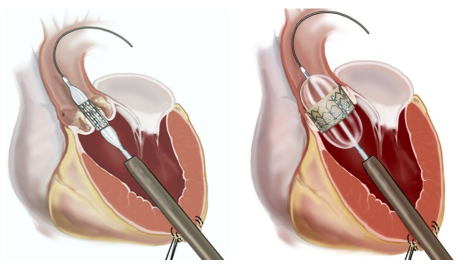

Fig. 1. Two schematic views of transapical aortic valve implantation (TA-AVI) show the aortic valve prosthesis placement (left) and the valve implantation (right) [3].

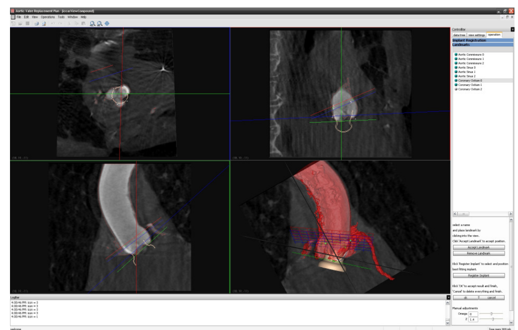

Fig. 3. Screenshot of the preoperative planning software: the surface of the aortic root is reconstructed and the optimal size and position of the aortic valve prosthesis (AVP) are selected.

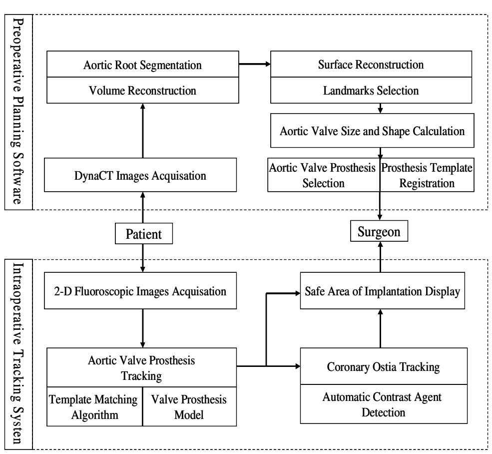

Fig. 2. Block diagram of the proposed image guidance system for assisting the TA-AVI.

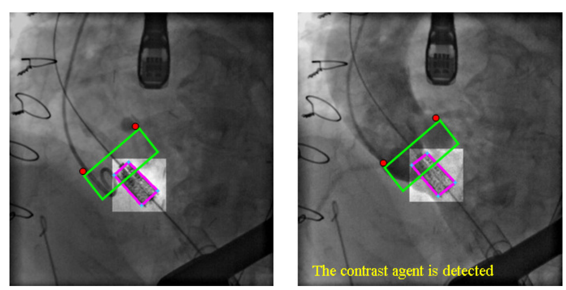

Fig. 4. Results of intraoperative tracking system for locating the AVP (in lighter intensity target window) and the coronary ostia (red points) in 2-D fluoroscopic images even without the contrast agent, the green box shows the safe area of implantation.