Perspectives on Image-Guided Transapical Beating Heart Aortic Valve Intervention

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Abstract

Image-guided interventional systems become an essential part of the modern minimally invasive surgical procedures, especially for the cardiac surgery. Transapical aortic valve implantation (TAVI) is a recently developed surgical technique to treat severe aortic valve stenosis in elderly and high-risk patients. The placement of stented aortic valve prosthesis is crucial and typically performed under live 2-D fluoroscopy guidance. To assist the placement of the prosthesis during the surgical procedure, a few image-guided TAVI systems have been developed. This work therefore presents current difficulties and challenges of these guidance systems, with consideration of future prospects.

Keywords

Aortic valve, minimally invasive cardiac surgery, C-arm CT system, X-ray fluoroscopy, computer-assisted intervention

1. Introduction

Transapical aortic valve implantation (TAVI) represents a recent minimally invasive alternative to the standard surgical treatment for the elderly and high-risk patients with severe aortic stenosis (AS). Compared to the standard aortic valve replacement interventions, the TAVI limits the surgical access to small incisions causing minimal tissue trauma. The TAVI technique is performed on the beating heart without cardiopulmonary bypass support [1]. Recovery time may be reduced and the patient can eventually return to normal activity more quickly.

In minimally invasive cardiac surgery performed today, Image-Guided Intervention (IGI) technology provides the physicians with invaluable insight of anatomical or pathological targets, based on modern imaging modalities such as computed tomography (CT), trans-esophageal echocardiography (TEE), magnetic resonance imaging (MRI) or X-ray fluoroscopy. The IGI systems employ computer vision methods to facilitate the performance of perioperative surgical procedures.

Interventional angiographic and fluoroscopic C-arm CT system is widely used to guide the TAVI procedures. Different IGI suites have been added to this C-arm system to perform integration combining 3-D information of diseased aortic valve from intra-operative CT

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images with live fluoroscopic images, but they have still some limitations to cover all clinical requirements, while increasing the overall safety for the TAVI surgery.

In the following, surgical and imaging methods of the TAVI are briefly reviewed. Also, the state-of-the-art in image-guided TAVI implantation is discussed, showing current difficulties and challenges in interventional support systems for the placement of stented aortic valve prosthesis. Finally, technical prospects for future work are concluded.

2. Clinical Background

In transapical beating heart surgical procedure, a stented aortic valve prosthesis (AVP) is temporarily crimped upon a balloon catheter and inserted via a left lateral mini-thoracotomy through the apex into the aortic root. After the valve is considered to be positioned correctly, the balloon-expandable prosthesis is deployed under rapid ventricular pacing to its final diameter, fixing the prosthesis in the aorta and pressing the natural calcified valve in the aortic annulus (Fig. 1). Once the AVP has been deployed, it cannot be repositioned. Hence, exact valve positioning is crucial.

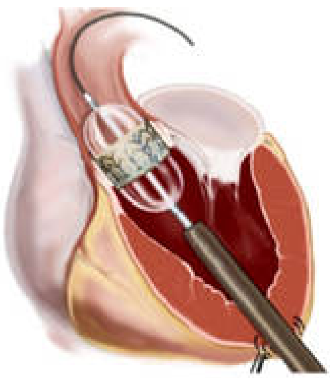

Fig. 1. Transapical beating heart approach for implanting the aortic valve Edward SAPIEN^{TM} prosthesis by instantaneous balloon inflation [Courtesy of Edwards Lifesciences Inc.].

3. Role of Imaging Modalities for TAVI

3.1. Preoperative Imaging

Echocardiography, multi-detector row computed tomography (MDCT) and MRI allow to quantify the severity of AS and are used to evaluate the following important factors for successful TAVI [2, 3]:

- Aortic valve morphology including tricuspid or bicuspid and calcifications
- Aortic annulus size measurement for selecting the appropriate prosthesis
- Coronary anatomy assessment for significant coronary artery disease
- Aorta and peripheral arteries evaluation including artery tortuosity and calcifications to ensure the suitability of transapical aortic valve approach

3.2. Intra-Operative and Follow-Up Imaging

Live 2-D X-ray fluoroscopy is mostly used during the TAVI, in order to determine proper valve positioning and the plane of alignment of the aortic valve cusps with supplemental echocardiography confirmation [3, 4]. Recently, an interventional C-arm CT imaging system (Siemens AG, Healthcare Sector, Forchheim, Germany) is used in the clinical routine to capture both intra-operative 3-D CT images and live 2-D fluoroscopic images. To start the surgical procedures of the TAVI, the physician uses the interventional C-arm CT system to reconstruct a 3-D CT image of the aortic root under a short episode of rapid ventricular pacing (RVP) from acquired rotational 2-D image sequences of 200^{o} over 5 seconds by applying 75 ml diluted contrast agent (Fig. 2b). In the presence of contrast agent, different fluoroscopic projections are used to visualize the aortic root and the aortic annulus in a perpendicular view (Fig. 2c). The annular plane is sometimes visible depending on the amount of annular calcification, but often only indirect clues are provided by the position of a pigtail catheter. The pigtail catheter should be placed at the bottom of a coronary sinus. Information from the planning CT or intra-operative C-arm CT images can be used to calculate the best possible fluoroscopic view for a coaxial implantation and automatically adjust the angulation of the C-arm without giving additional contrast agent. However, the following valve adjustment in the aortic annulus requires additional contrast agent and radiation exposure. When valve positioning is considered correct, the balloon expandable prosthesis is released to replace the diseased valve under RVP as shown in Fig . 2d. After the implantation, the assessment of the implanted AVP is also done by using fluoroscopy guidance (Fig. 2e).

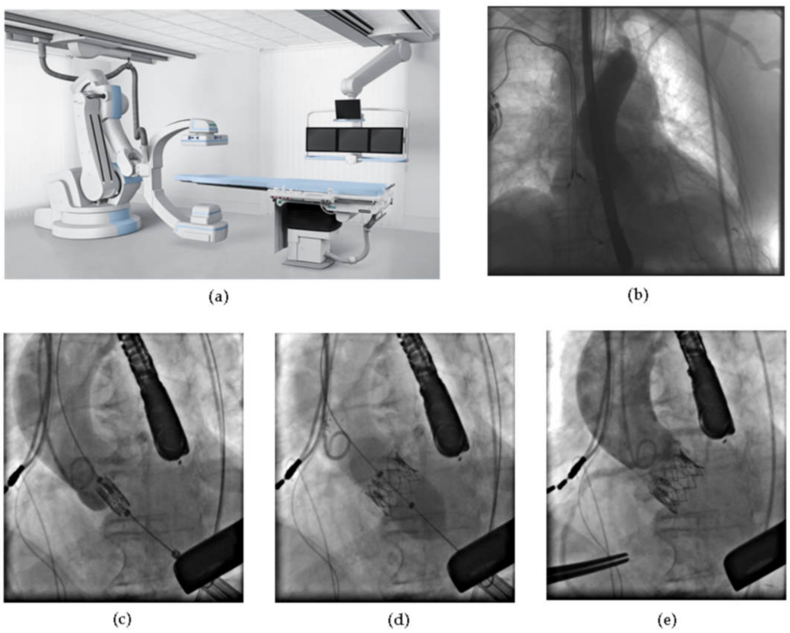

Fig. 2. (a) Fluoroscopy C-arm system (Siemens Artis Zeego, Forchheim, Germany). (b) Dyna-CT image. 2-D Fluoroscopy guidance during the TAVI procedures: (c) Valve positioning, (d) Valve implantation, and (e) Final assessment after valve implantation.

Real-time MRI has only been used experimentally to guide the TAVI in a porcine model [5]. The surgeon depends on the TEE to rapidly assess prosthesis position and function information. MDCT and MRI are used for follow-up examination to evaluate the prosthesis position after the implantation.

4. Image-Guided TAVI

4.1. Surgical Needs and Guidance Challenges

Intra-operative imaging is essential in coping with the surgical needs for the TAVI procedure. The physician uses mainly live 2-D fluoroscopy guidance to perform the valve positioning step as described above. However, the contrast quality of fluoroscopic images is generally limited to minimize the radiation exposure for the patient and the physician. The annular plane is sometimes invisible in live fluoroscopic images, depending on the amount of annular calcification. Therefore, the contrast agent is injected via a pigtail catheter to visualize the aortic root and the valve annulus in a few seconds. But the amount of contrast agent injection must be minimized to avoid renal insufficiency in elderly high-risk patients. Hence, some clinical requirements of 2-D fluoroscopy are proposed to further improve the guidance task of TAVI as follows [6].

- Limited dosages of contrast agent injection can be minimized by integrating a 3-D aortic root model from CT or intra-operative C-arm CT images with live fluoroscopic images, in order to overcome the visualization problem of the aortic root roadmap without contrast agent.
- Automatic estimation and visualization of target area for valve implantation presents a good assistance for the physicians, in order to accurately implant the AVP.
- Fully automated systems can be an ideal tool for intra-operative guidance of minimally invasive cardiovascular surgery. However, medical imaging systems provide interactive capabilities to allow the surgeon to control the display of guidance views, and to correct or minimize the unexpected errors if occurred. Therefore, recent imaging systems usually include some levels of user-interaction to ensure the safe surgical procedures.

4.2. Related Work

Only few previous studies related to image-guided planning and intra-operative support to assist TAVI. The research group of Prof. Terry Peters at the Imaging Research Laboratories, Robarts Research Institute (University of Western Ontario, London, ON, Canada) is working on developing approaches to register intra-operative images of the patient to use a navigation system that combines intra-operative TEE with a virtual model of instrumentation for the TAVI and/or other interventional cardiac procedures. They have proposed an approach for registration of real-time 3-D TEE and live fluoroscopy images to improve visualization during the TAVI [7]. This proposed approach includes 3-D TEE pose estimation from single-perspective fluoroscopic images. Point-based and intensity-based tracking techniques are used as two fluoroscopic image-based tracking techniques to localize a TEE probe, with a 2-D RMS registration error of 1.5 mm, and a tracking failure rate of below 1%.

Siemens (Healthcare Sector, Forchheim, Germany) and Philips (Philips Healthcare, Best, the Netherlands) have introduced two prototype systems to assist in planning and positioning the prosthesis using angiographic and fluoroscopic C-arm CT systems. Siemens has equipped its interventional C-arm with a system for automatic segmentation and overlay of aortic root volume including anatomical landmarks from intra-operative CT images on live 2-D fluoroscopic images [8]. Although it is a fully automatic guidance system, a level of user-interaction is needed to manually correct the 3-D positions of segmented valve landmarks such as the coronary ostia and lowest points of aortic cusps. The overlaid aortic root volume and the landmarks are static and do not follow aortic root motion during the surgical procedure. In a similar way, the guidance system of Philips; called HeartNavigator [9] provides the segmented CT data from different viewpoints allowing point-to-point measurements in any of these views as well as an appropriate selection of valve types and dimensions. During live fluoroscopy guidance, the fused visualization of the CT data rendering shows only the overlaid outline of the aortic root onto fluoroscopic images.

The group of Dr. Ming Li at the Bioengineering Section of Cardiothoracic Surgery Research Program, National Heart, Lung and Blood Institute (National Institutes of Health, Bethesda, Maryland, USA) have developed a prototype of a robotic assistant system for the TAVI under intra-operative MRI guidance [10]. Image-based robot registration was done using a compact fiducial that can be placed in the volume of interest. This robotic system has been only evaluated on a phantom.

Our research group at the Innovation Center Computer Assisted Surgery (ICCAS), University of Leipzig, Germany, has previously proposed an interactive TAVI guidance system including two separate modules which are a planning system and a fluoroscopic image-based tracking system [11]. The planning software has been developed to extract a surface model of the aortic root from the volumetric CT angiography and to virtually fuse a 3-D template of the prosthesis into the model. Image-based tracking of the AVP has been done based on template matching approach and on a shape model of the prosthesis. It was assumed that the motion of the AVP can be used to extrapolate the motion of the coronary ostia even without contrast agent. However, this tracking assumption is failed, if the surgeon pushed the prosthesis during the procedure.

4.3. Current Limitations of Fluoroscopy-Based Guidance Systems

A. Static CT Aortic Root Roadmaps Overlay

X-ray fluoroscopic images cannot distinguish soft tissue well. Thus integration of 3-D anatomic information from interventional CT system with live 2-D fluoroscopic images provides a helpful tool for the surgeon to easily define target positioning. However, fluoroscopic overlay image guidance of minimally invasive cardiac interventions is limited by the beating heart and the respiratory motions, causing misalignment between the static overlaid cardiac roadmap and the underlying anatomy. Therefore, different solutions to avoid this misalignment problem by directly using other imaging modalities, such as intra-operative 3-D echocardiography and real-time MRI guidance, or using advanced bi-plane fluoroscopy C-arm systems to generate 3-D and 4-D CT images. These advanced imaging modalities do not provide a good commercial solution to many heart centers. On the other hand, any imaging modality to fluoroscopy still needs 3-D-to-2-D registration to be performed, but it is a challenging task to obtain accurate results in real-time and without additional dosages of contrast agent as well.

B. Aortic Valve Prosthesis Tracking

Although tracking of interventional devices is a main key element of the IGI systems, unfortunately current TAVI guidance systems did not include the tracking of the stented AVP (John et al. 2010; Schröfel et al. 2010). In addition, localization of the prosthesis in live fluoroscopic images is a challenging task. The contrast in fluoroscopic images is generally limited to minimize the radiation exposure for the patient and the surgeon. The motion of the AVP is complex due to the heart beat under rapid pacing and the respiratory motion. Additionally, moving anatomical structures and guide wires in the image plane may interfere or overlap the AVP. The injected contrast agent to visualize the aortic root with the coronary ostia may obscure the view of the upper part of AVP during deployment.

C. Real-Time Image Processing and Visualization

Using high dimensional medical images or complex image processing and visualization algorithms can significantly slow down the update rate of processed live streaming images during the intervention. Consequently the availability of such surgical guidance systems cannot be ensured for the clinical use. In contrary, the power of modern GPUs allows the suitability of processing higher dimensional heart models and volume rendering of CT datasets [12]. Nevertheless, developing intra-operative image-guided systems still need to consider real timing and performance for overall system algorithms even without using the GPUs to achieve successfully surgical treatment procedures.

4.4. Our developed System for Guiding TAVI

Figure 3 shows our developed guidance system to assist the TAVI at the Heart Center Leipzig, Germany [13]. It augments a 3-D geometrical aortic mesh model and anatomical landmarks with live 2-D fluoroscopic images. The 3-D aortic mesh model and landmarks are derived from an interventional C-arm CT system. A target area for valve implantation is automatically estimated using these valve landmarks. Based on template matching approach, the overlay of 3-D aortic root model onto 2-D fluoroscopic images is updated by approximating the aortic root motion from a pigtail catheter motion without contrast agent. A rigid intensity-based registration method has been used to track the aortic root motion in the presence of contrast agent. The AVP is also tracked to assist the valve deployment. The evaluation results showed that the tracking errors are less than 2.0 mm and 0.5 for updating aortic root model overlay and for tracking the prosthesis respectively.

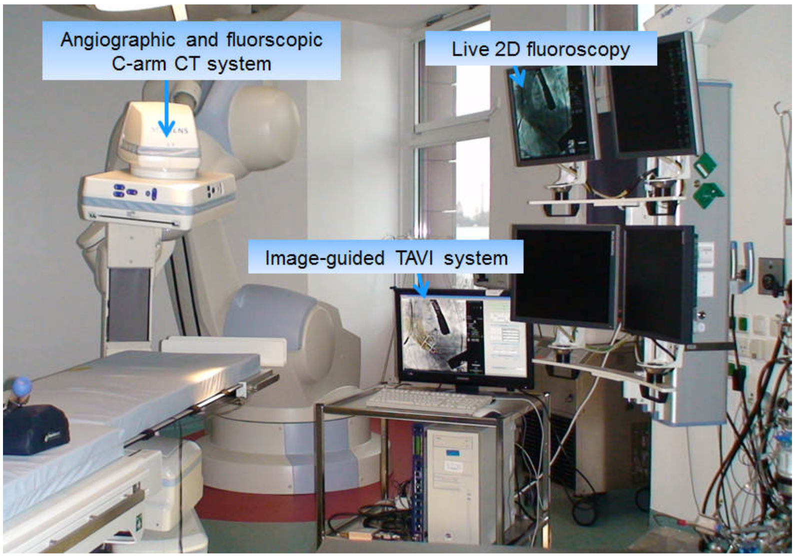

Fig. 3. Developed system setup in a "hybrid" operating room at the Heart Center Leipzig, Germany

5. Future Prospects

Further improvements of the image-guided TAVI systems can be achieved in the future as follows.

A. Aortic Root Modeling and Registration

The aortic root including the diseased valve has a deformable motion. Therefore, the modeling of the aortic root and landmarks can be extended from 3-D to 3-D+t meshes model by including the cardiac motion. Applying non-rigid registration methods, e.g. free-form deformations (FFD), can assist tracking of the aortic root in the presence of contrast. Consequently the updated overlay accuracy will be improved. Nevertheless, the hardware of the guidance system workstation must be upgraded in this case to keep the processing rate of live fluoroscopic images in real-time.

B. Intra-Operative Image Analysis and Visualization

Image-guided TAVI is mainly based on image analysis and visualization techniques, because using additional implanted radiopaque markers or external optical and electromagnetic tracking systems may complicate the surgical workflow. Hence, developing and improving software frameworks or toolkits are needed to process and to visualize live 3-D/4-D and 2-D imaging data during the interventions.

C. Surgical Robots

Developing a fluoroscopy-based surgical robotic system is one of future directions to perform the TAVIs. The above developed guidance system can present the main module to create such a robotic system. Mechanical and electronic valve delivery system will be operated based on the guidance results under supervision of the surgeons.

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