An Augmented Reality Environment for Image-Guidance of Off-Pump Mitral Valve Implantation

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ABSTRACT

Clinical research has been rapidly evolving towards the development of less invasive surgical procedures. We recently embarked on a project to improve intracardiac beating heart interventions. Our novel approach employs new surgical technologies and support from image-guidance via pre-operative and intra-operative imaging (i.e. two-dimensional echocardiography) to substitute for direct vision. Our goal was to develop a versatile system that allowed for safe cardiac port access, and provide sufficient image-guidance with the aid of a virtual reality environment to substitute for the absence of direct vision, while delivering quality therapy to the target. Specific targets included the repair and replacement of heart valves and the repair of septal defects. The ultimate objective was to duplicate the success rate of conventional open-heart surgery, but to do so via a small incision, and to evaluate the efficacy of the procedure as it is performed. This paper describes the software and hardware components, along with the methodology for performing mitral valve replacement as one example of this approach, using ultrasound and virtual tool models to position and fasten the valve in place.

Keywords: Minimally-invasive cardiac interventions, mitral valve implantation, image-guided surgery, virtual reality environment

1. INTRODUCTION

Somewhat surprisingly, early (1950s) cardiac procedures such as mitral commissurotomy and atrial septal defect (ASD) closure, were performed on the beating heart. However, since these operations were undertaken blindly, accuracy was very limited and the sub-optimal results were reflected in high morbidity rates.[1–3] Today, many cardiac interventions, including valve repair and replacement procedures have been conventionally performed through a median sternotomy, which provides generous surgical exposure and allows ample access to all cardiac structures and proximal major blood vessels. Over the past decade, advancements in cardiac surgery have occurred in response to technological advancements and the desire for less invasive approaches to surgery. Minimally-invasive surgical techniques have been developed to reduce surgical trauma and improve cosmetic results compared to traditional open-chest procedures. Patients undergoing these procedures have experienced a significant decrease in-hospital length of stay, less post-operative pain, faster recovery, and an overall faster return to the activities of normal daily living.[4]

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Improvements in endoscopic technology have resulted in a substantial increase in minimally-invasive surgery. Advances in closed-chest cardiopulmonary bypass (CPB) and myocardial preservation, as well as improved intracardiac visualization have stimulated the shift towards efficient and safe minimally-invasive cardiac procedures, which include percutaneous and robotically-assisted interventions.[5] Percutaneous mitral commissurotomy and valvuloplasty have been performed since the mid 1980s and have proved feasible for these applications. Balloon commissurotomy has been used extensively and provides good long- and short-term results in a wide range of patients. High-quality live imaging is the key for accurate assessment of cardiac valves and surrounding anatomy, as well as for successful intracardiac navigation of catheter-based therapeutic techniques.[6, 7] Today, mitral valve interventions on the arrested heart can be performed through small incisions using either endoscopic or robotic assistance. This trend has become a standard practice for an increasing number of cardiac surgeons in many worldwide medical centres. Innovations in computer-assisted telemanipulation in cardiac surgery led to complex reconstructive mitral valve operations that are performed completely using a robotic interface.[8]

Although the newer small-incision approaches increase patient satisfaction and reduce post-operative trauma, they do not eliminate the risk and cost associated with CPB, cardiac arrest and cardioplegia.[9, 10] One potential solution was proposed by McVeigh *et al.* in a recent study describing an approach in which real-time magnetic resonance imaging (MRI) is used to guide the insertion of a prosthetic aortic valve in the beating heart via direct apical access.[11]

In this paper, we describe an evolving technology that draws upon intra-operative imaging and virtual reality, aimed at performing targeted interventions inside the beating heart, without direct vision. The objective of our work is to develop and demonstrate a virtual environment that realistically represents the heart, and augments the standard ultrasound (US) view to provide the means to plan and guide minimally-invasive intracardiac interventions. To achieve this goal, we combine the readily available two-dimensional (2D) and three-dimensional (3D) US with a virtual representation of the surgical tools, both tracked in real-time, to provide a robust and accurate system for guidance inside the beating heart. The objectives and feasibility of our intervention system are described with respect to the implantation of a prosthetic mitral valve.

2. IMAGE-GUIDANCE PLATFORM: “NUTS AND BOLTS”

2.1. Intracardiac Access

For our artificial mitral valve implantation procedure, the intracardiac targets were accessed through the left atrial appendage using the Universal Cardiac Introducer (UCI)[12] (**Fig. 1**) affixed to the heart (i.e. left atrial appendage) via a minithoracotomy.

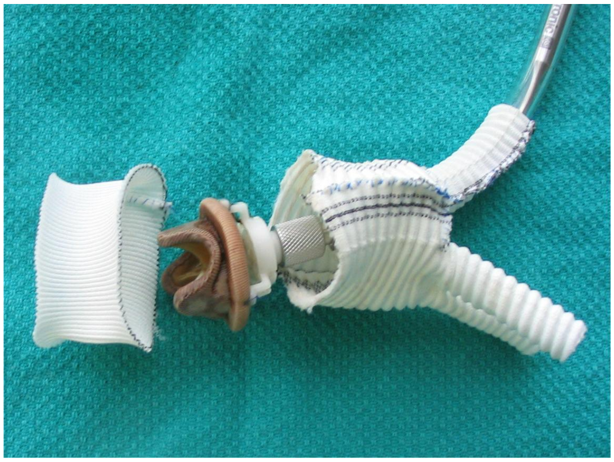

Figure 1. Universal Cardiac Introducer (UCI) and its components: the base cuff attached to the atrial appendage, and main chamber equipped with three sleeves that accommodate various surgical instruments. As an example, a valve-insertion tool with the attached prosthetic valve is shown in the figure.

The UCI had previously undergone extensive testing using animal studies to demonstrate its feasibility for endocardial ablation for atrial fibrillation, and mitral valve implantation. This device provides safe port access to intracardiac cavities and targets, and can be removed at the end of the intervention. The UCI is designed as an "air lock" between the blood-filled cardiac cavities and the atmosphere of the chest, and it consists of an insertion cuff, attached at one end to the atrial appendage, and at the other end to the introductory chamber. This chamber has sleeves that allow the introduction of up to four different surgical instruments (eg. laparoscopic tools, pressure line, endoscope, etc.). For mitral valve implantation, the sleeves of the introductory chamber accommodate the valve-insertion tool, a pressure line, and a valve-fastening device. The introducer is safe and versatile and does not extensively compromise the manipulation of tools.

2.2. Image-Guidance

2.2.1. Echocardiography Guidance

The feasibility of intracardiac procedures using our cardiac port access device was demonstrated in several animal studies. To compensate for the lack of direct vision inside the beating heart, we employed a 4-7.5 MHz 2D TEE US probe for intra-operative visualization of surgical instruments and target. To further assist in visualization, a 3D trans-thoracic echocardiography (TTE) probe was used to acquire images from the epicardial surface, in addition to an intracardiac echocardiography (ICE) catheter introduced into the right atrium via the left internal jugular vein. Suematsu *et al.*[13] also raised the necessity of employing 3D echocardiography as a technique superior to 2D US for guiding instruments within the beating heart. They reported their experience using only 3D US, without the benefit of a virtual environment, as the guidance platform in a laboratory environment.

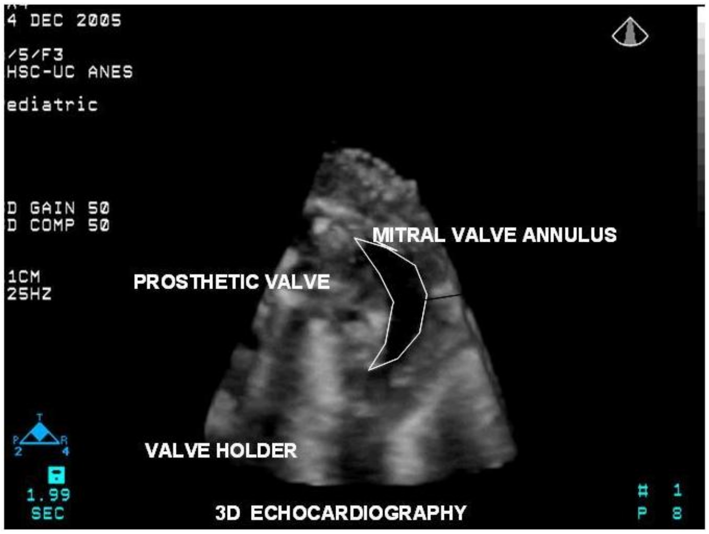

Figure 2. 3D US image showing the mitral valve annulus, prosthetic valve, and valve-insertion tool. Note the difficulty of correctly interpreting the anatomical features and surgical tools.

Our initial experience in valve placement through the left atrium into the mitral valve orifice relied on US image-guidance alone, and emphasized the significant constraints imposed by the low quality of the 2D US images. The placement of the valve in its correct target location involved a great deal of trial-and-error, with the final positioning of the valve requiring the use of a large, dynamic 3D US transducer placed on the epicardium. Unfortunately, not only are such devices bulky and compromise the access to the target, but also they have a small field of view, and real-time visualization is confined to the US imaging system itself, without offering the possibility of extracting the 3D data for further manipulation in an independent system.

Based on these studies, we concluded that the use of 2D TEE guidance has significant disadvantages when used as the sole modality for image-guidance. Both anatomical targets and surgical tools are poorly perceived in US images, making it impossible to assess their position and orientation during manipulation, especially since the 2D cross-sectional images do not provide the necessary context within the 3D cardiac anatomy. Some of the frequent questions arising during the procedure referred to whether the prosthetic valve was within the mitral orifice or whether the valve skirt was in contact with the valve ring, and answering them was challenging even to an experienced surgical team (**Fig. 2**). These limitations can be addressed by augmenting the 2D dynamic US image-guidance with a 3D virtual representation of the target, surrounding anatomy, and surgical tools. This approach offers the advantage of intra-operative real-time imaging, while employing only standard 2D echocardiography.

In spite of its limitation with respect to image-guidance, the Doppler capabilities of US are ideal for assessing the intervention. Abnormalities in flow patterns, such as regurgitant flow through or around the mitral valve seat, or incomplete ASD repair, can be easily detected.

2.2.2. Augmented Virtual Reality Environment

While our early studies clearly emphasized the limitations of TEE as a sole intracardiac image-guidance tool, we identified the need to complement the US with additional features. We therefore developed a system that permits the display of the 2D US images within the context of 3D cardiac anatomy obtained from pre-operative CT or MRI volumes, along with virtual representations of the surgical tools.

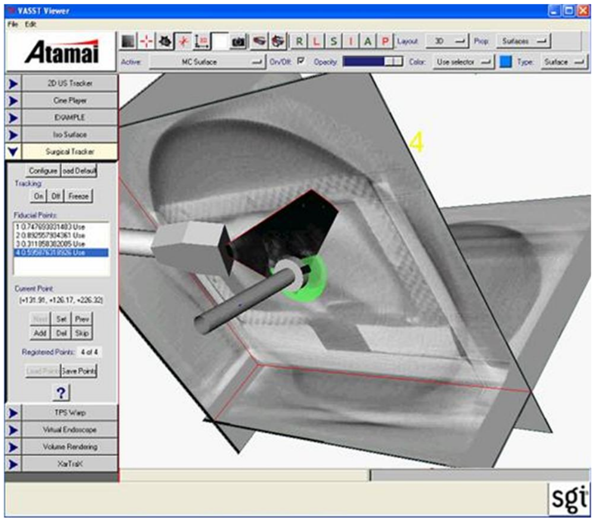

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Figure 3. Screen shot of the "AtamaiViewer" platform, showing the integration of pre-operative models, intra-operative US imaging, and valve-insertion tool.

The development of our image-guidance platform takes place within the Virtual Augmentation and Simulation of Surgery and Therapy (VASST) Laboratory at the Robarts Research Institute. Over the past years, many tools and techniques have been developed, which are now incorporated in the current project. The primary visualization tool is the "Atamai Viewer", designed to integrate all components necessary for image-guided interventions, including image registration,[14] cardiac modeling,[15] dynamic MRI-US image registration,[16] and procedure planning.[17] Our software platform integrates the visualization of pre-operative multi-modality images with intra-operative US, endoscopic data, tracked surgical tools, haptic devices and virtual models (**Fig. 3**). It provides the ability to selectively combine the different imaging components and overlay them using different levels of transparency, display volumetric data on orthogonal or oblique planes, and visualize dynamic data as cine sequences. The viewer also permits the incorporation of optical and magnetic tracking systems in a common virtual workspace for a single application, and is designed to support stereoscopic visualization. In addition, the modular design of the platform facilitates the ready addition of new components and features.

Three tracked objects are needed for the mitral valve implantation procedure: one for tracking the TEE probe, one for tracking the valve-insertion tool, and a third for determining the position and orientation of the valve-fastening device. **Fig. 4** illustrates the prosthetic valve to be implanted attached to the valve-insertion tool, accompanied by its virtual representation. A similar realistic virtual representation was designed for the US transducer, as well as the valve-fastening tool.

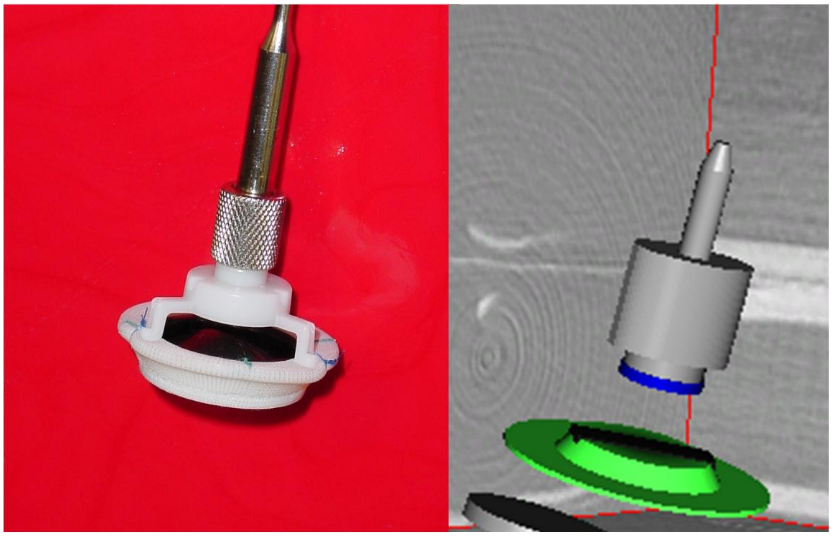

Figure 4. a) Diagram illustrating the physical representation of the prosthetic mitral valve attached to the valve-insertion tool (left); b) Virtual representation of the valve and valve-tool (right).

2.2.3. Tool Tracking

For the mitral valve implantation procedure, the positions and orientations of the TEE probe, the valve-insertion tool, and the valve-fastening device were tracked in real-time. To ascertain the position of an US image in space relative to the subject, the transducer must be tracked relative to a coordinate system. When the US transducer is hand-held, optical tracking may be employed. However, during most cardiac applications echo- images are acquired via a TEE transducer (introduced in the esophagus, dorsal to the heart) or even inside a heart chamber itself (ICE probe). Since line-of-sight is not available in these cases, optical tracking is not feasible and a different approach must be used instead. For our application we track both the US transducer and surgical instruments using a magnetic tracking system (MTS) - the NDI Aurora. This system identifies the position and orientation of miniature 5 or 6 Degree-of-freedom (DOF) sensors fixed to the transducer and tools, respectively, through measurement of magnetic field pulses emitted by a closely-placed magnetic field generator.

The AtamaiViewer software platform has many tools for calibration of both tracked surgical tools and US transducers. In the present study, the tracked US probe was calibrated using a Z-bar device. The valve insertion tool was calibrated by first defining a transform for the tool tip and orientation without the valve being attached. A similar procedure was used to calibrate the valve-fastening tool. In addition, a reference MTS sensor was attached to a stationary region of the subject to avoid the need to recalibrate the “world” coordinate system in case of accidental motion of the subject or field generator. A complete representation of the virtual environment containing all tracked tools is shown in **Fig. 5**.

3. EXPERIMENTAL METHODOLOGY

To illustrate the efficiency of our virtual environment in conducting intracardiac interventions in the absence of direct vision, we designed two sets of experiments. The former consisted of the “implantation” of a prosthetic mitral valve into the “mitral annulus” of a cardiac intervention phantom, as described in section **3.1**. In the latter set of experiments, the same procedure was performed, but this time on an excised porcine heart (section **3.2**). The task was to guide the valve mounted on the insertion tool, place it on the target, and secure it in place using a laparoscopic suturing tool.

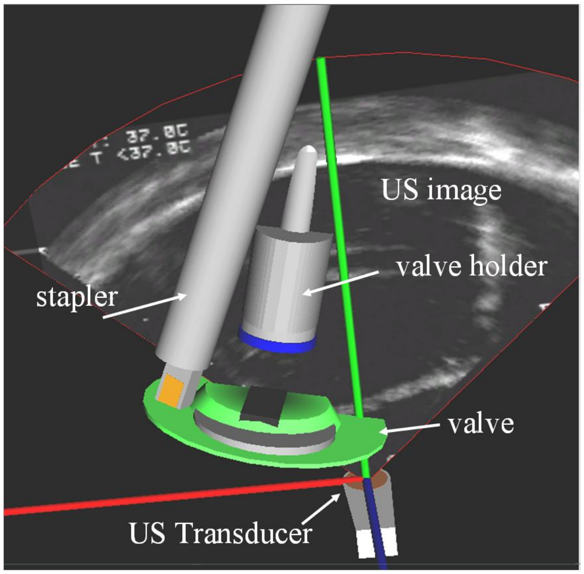

Figure 5. Virtual environment showing mitral valve, valve-insertion tool, valve-fastening tool, 2D US probe and image.

3.1. Cardiac Intervention Phantom

We constructed a cardiac intervention phantom (**Fig. 6**) similar in concept to that described by Rettmann *et al.*,[18] made from non-magnetic materials to minimize the interference with the tracking system. A tube descends into the lower part of the phantom simulating the esophagus and facilitating the use of TEE probes. Cardiac tissue was mimicked using poly-vinyl alcohol-cryogel (PVA-C) membranes[19] supported by plexiglass plates. This phantom provides a means of assessing newly-developed intervention procedures under image-guidance, with progress being monitored using endoscopic inspection of the target. For our application, the phantom facilitated the testing of new tools, surgical techniques, and skills in a laboratory that closely mimic real clinical settings, reducing the reliance on animal studies.

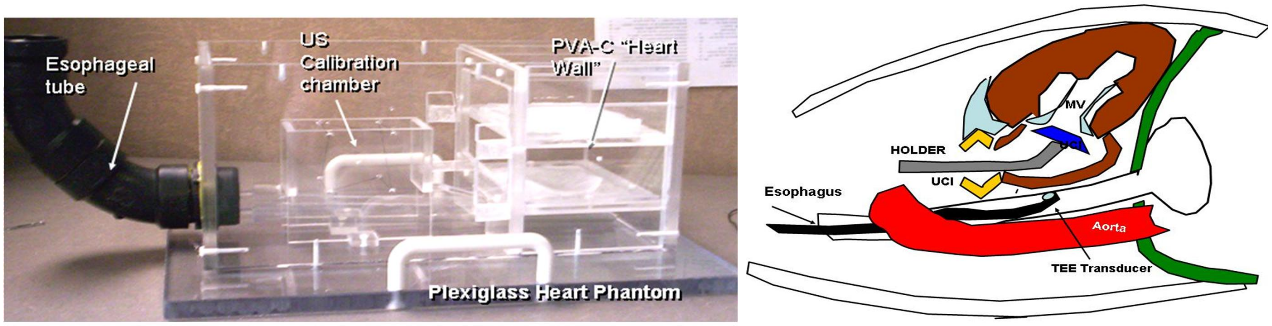

Figure 6. Plexiglass heart phantom showing "esophagus" and membranes representing heart wall tissue (left); Equivalent schematic representation of cardiac anatomy (right).

3.1.1. Valve Positioning

A first set of studies examined the accuracy with which an experienced surgeon could place the valve on target under 2D US guidance alone, and with US complemented by the virtual representation of the valve and its insertion tool. In this case, the target was represented by a 2 cm. diameter hole in a pliable PVA-C membrane that could deform under pressure from the valve and tool as the valve was being manipulated. Besides the tracked objects, our virtual environment included a CT volume of the cardiac phantom, all registered to the physical phantom. In addition, a virtual target (a 2 cm. disk) was interactively outlined from the 2D US images and displayed within the volume. Although the target is represented in the pre-operative model, because of the pliability of the artificial membrane material, as seen in the pre-operative scans, it is unlikely to be precisely registered with the actual target.

Under US-guidance alone, the valve insertion-tool may be identified by depicting the sonic reflections from its intersection with the image plane. Although a few characteristics of the tool may be appreciated, it is extremely difficult to determine its exact position and orientation with respect to the target. However, when the echo image was complemented by the virtual representation of the tool and displayed in the context of the 3D pre-operative model, navigation of the valve towards the target became almost trivial.

3.1.2. Valve Fastening

Once the surgeon placed the valve on target, its position was confirmed using 2D intra-operative US images. The procedure was finalized by securing the valve in place, using a valve-fastening device that inserted clips through the valve skirt and into the mitral annulus. This task was first attempted using US guidance alone, followed by navigation using the hybrid US/VR environment. After determining its location in space with respect to the valve, the fastening tool was guided towards the target using the virtual models. Its positioning on target was refined using real-time 2D US and then the clip fastener was introduced. The valve was secured to the underlying membrane by applying clips at multiple locations around the valve skirt.

3.2. Excised Porcine Hearts

The second set of experiments was similar to those conducted on the cardiac intervention phantom, however, in this case an excised porcine heart was used instead of PVA-C simulated cardiac tissue. The intact heart was excised from the chest of a pig at the end of an animal study, rinsed thoroughly with saline solution and refrigerated for three days prior to the experiment. Our objective was to perform the mitral valve implantation procedure on a realistic cardiac subject in the context of real anatomy, while confirming the limitations of US image-guidance and emphasizing the benefits of our virtual environment for intracardiac navigation.

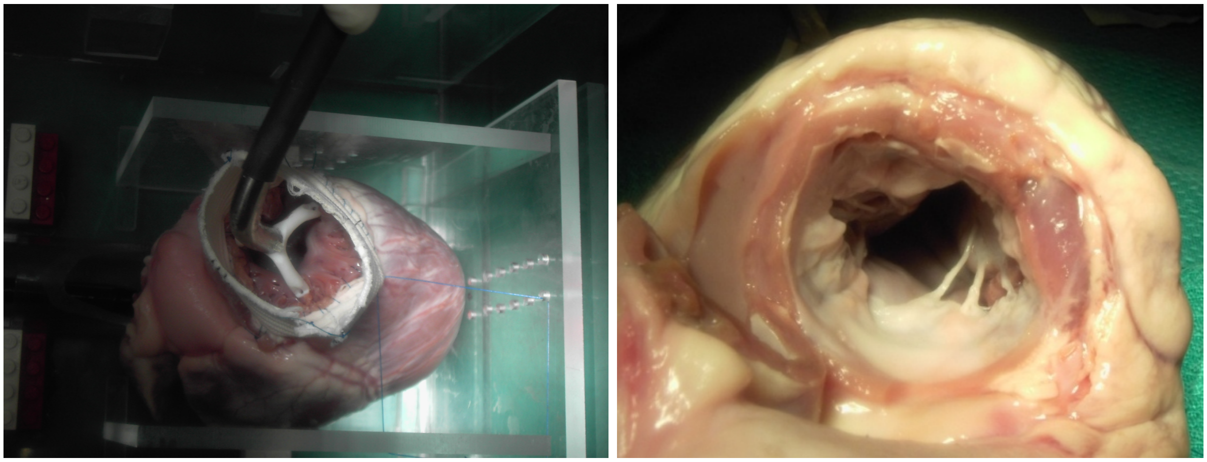

Figure 7. a) Mounting of the excised heart inside the phantom according to experimental procedure. Note the attachment of the UCI to the heart for intracardiac access (insertion cuff already sutured attached to the left atrial appendage (left); b) Short-axis view of the native mitral valve annulus and parts of the valve leaflets attached to the chordae tendinae in an excised heart (right). The mitral annulus represents the target onto which the prosthetic valve must be placed and fastened during implantation.

The heart was mounted inside the cardiac phantom and supported using plexiglass plates. To prevent any rigid body translation and rotation, the heart was anchored in place using a 3 point support (2 lateral and 1 basal), with the apex resting freely on the bottom of the vessel. In order to simulate its *in situ* orientation during the intervention, the heart was positioned with the left atrium facing upwards, as shown in **Fig. 7a**. Intracardiac cavities were reached using the UCI through the left atrial appendage.

Intra-operative real-time 2D US images were acquired using the TEE probe descended into the cardiac phantom through the "esophagus". The virtual environment consisted of the pre-operative CT volume of the phantom, along with a virtual representation of the US transducer, the valve-insertion tool and the valve-fastening device, all registered within the same coordinate system. The target consisted of the anatomical mitral valve annulus (**Fig. 7b**), whose size was estimated from a short-axis view of the native mitral valve.

4. PROCEDURE OUTCOME AND ASSESSMENT

4.1. Cardiac Phantom Results

Several experiments were performed to position and secure the valve on target under both 2D US alone, and using the US/VR environment. The procedure was blinded, with results being visualized using an endoscope directed at the target. The procedure was performed by a surgeon (GG) and an echocardiographer (DB), both with extensive experience in mitral valve interventions. The challenges encountered during US-based valve guidance were consistent among all trials, and underlined the difficulty of identifying the exact target and tool location. During the placement of the prosthetic valve, positioning that seemed to be correct proved to be several mm off-target, in both translation and angulation (**Fig. 8a**). The "US-only" experiment lasted for approximately 30 minutes and proved unsuccessful; 4 clips were fired using the laparoscopic clip-applier, however, none of them managed to efficiently fasten the valve skirt to the underlying membrane.

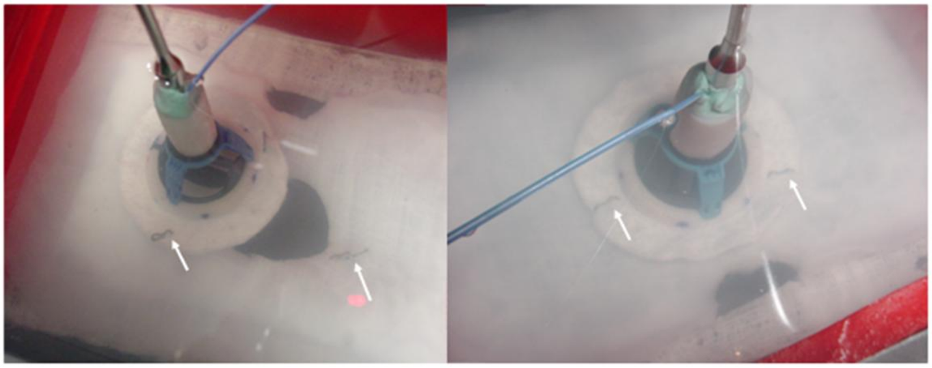

Figure 8. a) Poorly placed and secured valve under US guidance only (left); b) Correct valve positioning and fixation under US/VR guidance (right). In both cases, arrows indicate the clips.

In contrast, when using the hybrid US/VR system, the surgeon managed to guide the valve on target with very little difficulty while relying mostly on the virtual environment, and employed 2D US only to refine the position of the valve once on target. Similarly, the VR was very helpful during guidance of the fastening device toward the target, while intra-operative 2D echo- images were useful to ensure the clip was accurately applied in the desired location (**Fig. 8b**). These trials were performed by the same experienced clinicians during an average time of 4 minutes. As a result, the valve was properly positioned onto the "valve-seat", and successfully attached to the PVA-C membrane.

In summary, during these trials, none of the positioning/fastening attempts under 2D US image-guidance alone were successful (i.e. either valve and/or clips were misplaced). However, when the intra-operative 2D US images were augmented with the virtual reality environment, a 100 % success rate was achieved.

4.2. Excised Heart Results

After evaluating the feasibility of our hybrid surgical navigation system using the cardiac intervention phantom, we performed our next experiment in a more clinically-relevant environment. The surgical team performed the mitral valve implantation on the excised porcine heart in the operating room, under conditions that mimicked an *in vivo* procedure. Intracardiac access was achieved using the UCI through the left atrial appendage, which accommodated the valve-insertion tool, valve-fastening tool and endoscopic camera for intracardiac assessment in the absence of direct vision.

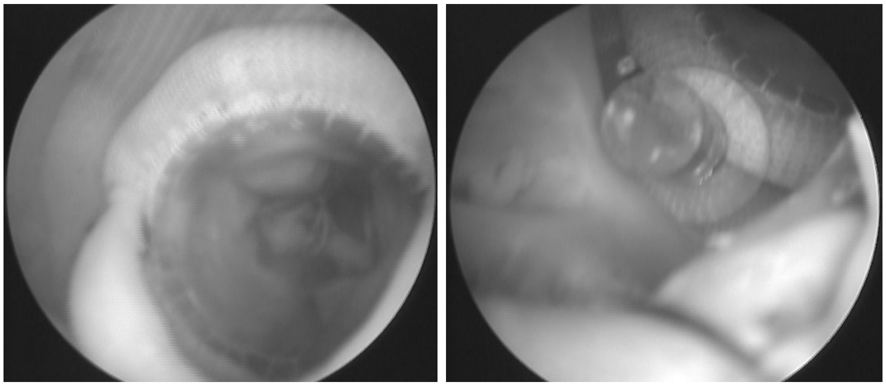

Figure 9. a) Endoscopic view showing the placement of the prosthetic valve on target under US guidance (left); b) Endoscopic image illustrating the position of the clip applied to attach the valve to the underlying tissue (right).

Under sole use of US image-guidance, the prosthetic valve was placed into the left ventricular in-flow tract of the heart. The 2D US images were rather misleading even to the experienced surgeons, causing them to rely on previous experience in the clinic. After successive trial-and-error attempts, when it was determined that the valve was in place, the endoscopic camera was employed to assess the position of the valve with respect to the anatomical target (**Fig. 9a**). The next step was to secure the valve in place using a push-pin device, relying only on 2D US images. Another endoscopic assessment followed by direct observation revealed that only one pin was applied in the right location, while attaching the valve to the underlying tissue (**Fig. 9b**). The other three clips were off-target (1 was in the centre of the valve, while 2 others punctured the ventricular wall).

In the next stage, the surgeon made use of the augmented representations of the surgical instruments for intracardiac navigation. The "operating field" was displayed stereoscopically using head-mounted displays, providing the surgeons with a better spatial perception of the virtual environment. Guiding the valve to the mitral annulus using the hybrid US/VR system was a relatively simple task, and once on target, its position was fine-tuned according to the US images. This success was confirmed by an endoscopic evaluation (**Fig. 10a**). Typically, the valve seating was much closer to the ideal under these conditions.

Furthermore, when valve fastening was complemented by the virtual representation of the target and suturing device, the operator found it much easier to place the tip of the tool closer to the final target initially, and refine its position based on the TEE images. Four pins were used in the attempt to "suture" the valve to the underlying tissue, and according to our endoscopic assessment (**Fig. 10b**), as well as the direct observation (**Fig. 10c**), three of them were positioned at their proper location, while securely attaching the valve. The fourth pin, although properly located, did not penetrate into the mitral annulus tissue due to interference with the ring of the prosthetic valve.

In conclusion, the procedure executed on the excised heart confirmed and matched the results previously obtained using the cardiac intervention phantom. According to our observations, the most helpful characteristic of the virtual environment was its ability to visualize the entire 3D perspective of the surgical tools, their position and orientation relative to the target, information not immediately and clearly available in either 2D or 3D US images.

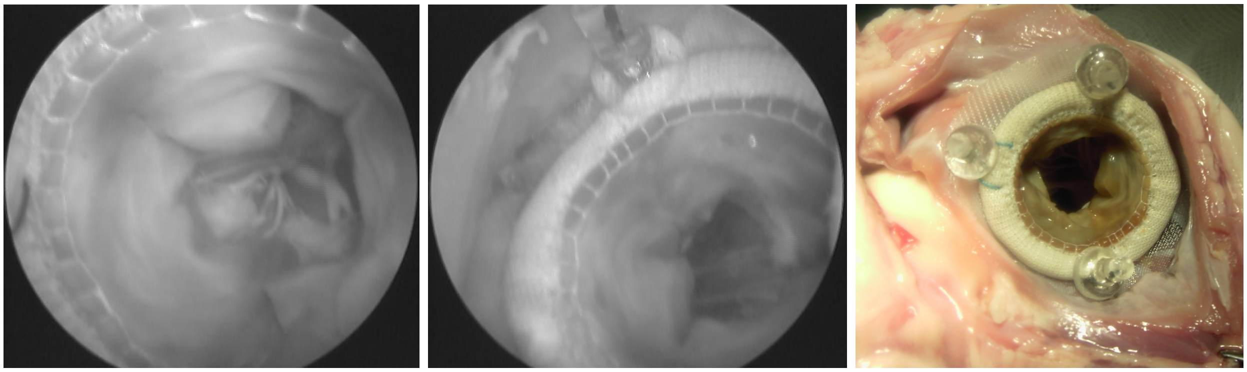

Figure 10. a) Endoscopic image showing the success in positioning the valve onto the native mitral annulus using the hybrid US/VR system. Appropriate positioning is confirmed by the clear view of the chordae tendinae in the background (left); b) Endoscopic image showing one of the pins used to attach the valve to the native annulus (centre); c) Image acquired at the completion of the procedure under direct observation (right). Note the correct location of the fastening pins around the mitral valve achieved under US/VR intracardiac guidance.

5. DISCUSSION

To date we have performed several studies on the cardiac intervention phantom in the laboratory, which underlined the benefits of the augmented US and VR system not only from the operators' perspective, but also by judging the outcome of the procedure. To better mimic the environment during a real procedure, we performed similar studies on the cardiac phantom in the operating room. This experience allowed us to determine some of the limitations we might encounter during a "live" intervention. In addition, we have recently performed several intracardiac interventions on porcine subjects in the operating room, although it is too early to report specific results. Intra-operative US was used to define the *in vivo* mitral valve annulus, the VR environment assisted in directing the surgical tools to specific targets, while final positioning was achieved under real-time US guidance. These studies added significant insight relating to some of the challenges that we might expect to face during the translation to the clinical studies. Currently, we are working on optimizing tool design to better accommodate the magnetic trackers, as well as further adapting our navigation system for live intracardiac interventions.

As previously mentioned, a "busy" environment is not unusual in an operating room, in which case the use of a magnetic system for tool tracking is superior to an optical system. However, given that the tracking accuracy of a magnetic system decreases when moving away from the magnetic field generator due to field inhomogeneities, it is imperative that the field generator be placed within a range of 10-20 cm from the most probable tool location. This setup might obstruct the regular "task flow" of the clinical staff. In addition, in order to minimize the tracking error, the tracked tools should be manufactured from non-ferromagnetic alloys (e.g. high-grade stainless steel or plastic), and also avoid the presence of other ferro-magnetic objects in close proximity to the electromagnetic field emitter.[20]

The size of the surgical instruments used in the intervention give rise to another set of constraints. In our applications, intracardiac cavities are accessed through the left atrial appendage, using the UCI. As such, a slightly larger prosthetic mitral valve may be difficult to insert through the small orifice between the atrial appendage and left atrium. Another potential challenge regarding the instrument size may be reflected in the surgeon's dexterity in maneuvering the valve-insertion tool and the fastening tool not only inside the the UCI, but also within the heart itself. Ideally, the clip-applier should always be situated above the prosthetic valve, as it is used to attach the valve skirt to the mitral annulus. Finally, we must design tools and devices that deliver the required treatment to the target while being compatible with standard imaging and tracking systems. Furthermore, the clip-applier currently employed in securing the valve in place will likely be replaced by other more suitable fixation devices, such as the one suggested by Downing *et al.*.[21]

As our described technique constitutes a novel approach to intracardiac surgery, it is important that the information be presented to the surgeons in a familiar manner. While the visualization environment brings together the TEE image-guidance, augmented by the virtual representation of the surgical tools, one question that may arise is how the multi-modality data set should be presented to the operator. Should the image be displayed on a simple computer monitor, on a flat screen overlaid onto the patient located directly above the operating field, on a stereoscopic screen that enables 3D visualization, or a head-mounted display which allow the surgeons to directly "navigate" within a virtual volume, as suggested by Sauer *et al.*[22] or Birkfellner[23]? While we have already tackled some of these issues, others, such as those related to tracking and registration accuracy will be addressed in the future work.

6. CONCLUSIONS

This project is still in its infancy, and a great deal of additional work remains to be performed, including instrumenting the phantom to simulate cardiac motion and blood-flow. However this early series of experiments has convinced us that the use of a VR system can significantly enhance the surgeon's ability to navigate within body cavities when direct vision is not available. It has also suggested that the virtual environment is much more important when establishing the initial position and orientation of the intervention tools, than it is to perform the final targeting, which is refined under the control of the US images, in spite of their limitations.

The general conclusion, based upon both the target localization and valve positioning studies, was that the virtual environment significantly assisted the operator in completing the task. When using US guidance alone to position the clip-applier and fix the valve to the underlying membrane, the procedure proved to be complex and largely unsuccessful. However, when the same task was attempted using the hybrid US/VR system, it became almost trivial.

The use of the VR environment can be a key element to enhance the performance of off-pump beating heart intracardiac surgery. Augmented with US imaging for final positioning, this combination provides extensive support for target visualization, planning optimal routes to the target, and guidance for directing therapeutic interventions. This initial work has demonstrated the tremendous potential of multi-modality imaging, combined with tracking of tools and real-time US for providing the capability to both visualize and assess the surgical intervention in a manner that will ultimately be superior to direct vision, within its inherent limitations.

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