Cardiac Imaging and Modeling for Guidance of Minimally Invasive Beating Heart Interventions

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Abstract. Minimally invasive beating heart intracardiac surgery is an area of research with many unique challenges. Surgical targets are in constant motion in a blood-filled environment that prevents direct line-of-sight guidance. The restrictive workspace requires compact, yet robust tools for proper therapy delivery. Our novel method for approaching multiple targets inside the beating heart allows their identification and access under augmented reality-assisted image guidance. The surgical platform integrates real-time ultrasound imaging with virtual models of the surgical instruments, along with virtual cardiac anatomy acquired from pre-operative images. Extensive *in vitro* studies were performed to assess the operator's ability to "deliver therapy" to dynamic intracardiac targets via both transmural and transluminal access, and demonstrated significantly more accurate targeting under augmented reality guidance compared to ultrasound image guidance alone, accompanied by a reduction of procedure time by half. Moreover, preliminary *in vivo* acute studies on porcine models showed successful prosthesis positioning for beating-heart septal defect repair and mitral valve implantation via direct surgical access. While still in its infancy, this work emphasizes the promise of ultrasound-enhanced model-guided environments for minimally-invasive cardiac therapy, whether delivered via a catheter introduced into the vascular system or a cannula inserted through the heart wall.

1 Introduction

Intracardiac procedures have challenged surgeons and researchers ever since the pioneers of modern cardiac surgery performed the first interventions on the beating heart [1,2], as their outcome was compromised by inadequate visualization of intracardiac structures. Thanks to recent developments in image-guided surgical techniques, cardiac surgery has benefited from reduced trauma and shorter recovery times for patients [3]. Nevertheless, minimizing invasiveness has inevitably led to more limited visual access to the target tissues. While incision sites have been reduced, and robotic and laparoscopic technologies have been introduced to minimize tissue exposure, most intracardiac interventions are still performed under cardiopulmonary bypass, which may lead to adverse effects [4,5].

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Image-guided surgery (IGS) relies on the assumption that pre-operatively acquired images provide a sufficiently accurate representation of the intra-operative anatomy to guide the procedure. However, this assumption is not necessarily valid for most soft tissues, and it definitely poses a significant issue in cardiac applications. Considering the large myocardial deformations encountered during interventions, intra-operative imaging is indispensable to provide real-time information on the anatomical changes, and is often employed in the operating room (OR). Moreover, stereoscopic, virtual (VR) and augmented reality (AR) techniques have been implemented to enhance visualization and surgical guidance.

We have developed a novel surgical guidance package to facilitate therapy delivery on the beating heart. Our platform relies on trans-esophageal echocardiography (TEE) for real-time intra-operative guidance, pre-operative cardiac models for anatomical enhancement, and magnetic tracking technology for real-time tracking of surgical instruments [6]. As a result, clinicians can explore the intracardiac environment in real-time via US, using the registered pre-operative models as guides, and navigate tracked surgical tools intuitively relative to the 3D cardiac anatomy [7]. We envision that VR-enhanced ultrasound (US) guidance will eliminate the need for intra-operative fluoroscopic imaging and allow the fusion of surgical planning and guidance [8,9].

This paper provides an overview of our VR/AR-based surgical guidance platform, the development and integration of various components, the evaluation of the environment, and finally its translation from the image-guided surgery laboratory into the operating room.

2 Surgical Platform

2.1 Architecture

Our surgical guidance platform integrates a wide variety components for IGS applications, including multi-modality image visualization, anatomical modeling, and surgical tracking. Moreover, given the lack of visualization during off-pump surgery, we used this system to build an AR environment to provide surgeons with a virtual display of the surgical field that resembles the real intracardiac environment.

2.2 Augmented Reality Environment

The origins of our augmented reality surgical platform arose from the desire of our surgeon colleagues to develop a procedure for implanting a prosthetic mital valve inside the beating heart. Not only did they require a means of introducing multiple tools into the cardiac chambers, they also needed to manipulate and visualize these devices in real time.

Ultimately, transmural surgical access was enabled via the Universal Cardiac Introducer(UCI)©- a device that is attached to the heart chamber and acts as an “air-lock” between the blood-filled cavity and the chest, enabling the positioning of surgical instruments, introduced into the throacic cavity via a mini-thoracotomy, inside the beating heart. Moreover, we proposed an intracardiac visualization approach that relied on intra-operative echocardiography for real-time imaging, augmented with representations of the surgical tools tracked in real-time and displayed within anatomical context available from pre-operative images. By carefully integrating all components, such an environment is capable to provide reliable tool-to-target navigation, followed by accurate on-target positioning.

Intra-operative Imaging: Echocardiography. Ultrasound is widely employed as a standard interventional imaging modality. Specifically, 2D TEE provides good-quality images and eliminates the interference between probe manipulation and surgical work-flow. However, the main drawback is its inability to depict sufficiently crisp representations of the anatomical targets and surgical tools. While such limitations may be tolerable in *in vitro* studies performed in a laboratory environment under ideal conditions, they are highly amplified in a clinical setting by the complexity and variability of the anatomy, image quality, and orientation of the US beam with respect to the anatomy (Fig. 1). To address these problems, we augment the 2D intra-procedure images with anatomical context supplied by the pre-operative models generated from CT or MR images acquired prior to the intervention.

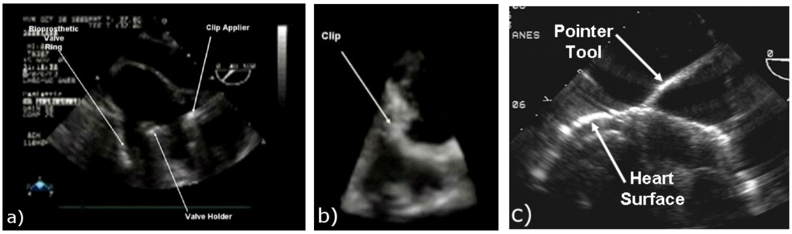

Fig. 1. a) 2D TEE image of the valve tool and clip applier inside a beating porcine heart; b) 3D US image of a similar scene; 2D TEE image of *in vitro* phantom study. Note the difficulty in interpreting the anatomical features and surgical tools.

Pre-operative Modeling. For *in vitro* studies involving cardiac phantoms, we rely primarily on pre-operative CT images for model building, given their good image contrast and temporal resolution, and make use of automatic techniques for image segmentation, such as the Vascular Modeling Toolkit[1]. On the other hand, once translating to clinical porcine studies, the insufficient contrast between cardiac structures provided by CT without contrast enhancement forced us to resort to the use of MR images. Their excellent soft tissue characterization facilitated the of anatomical feature identification, leading to better quality

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[1] VMTK: http://www.vmtk.org

subject-specific models. We first model each cardiac component, then assemble them together according to the complexity of the procedure. Typically, the main features of interest include the left ventricle myocardium (LV), the left atrium (LA), the right atrium and ventricle (RA/RV), and aorta (Ao).

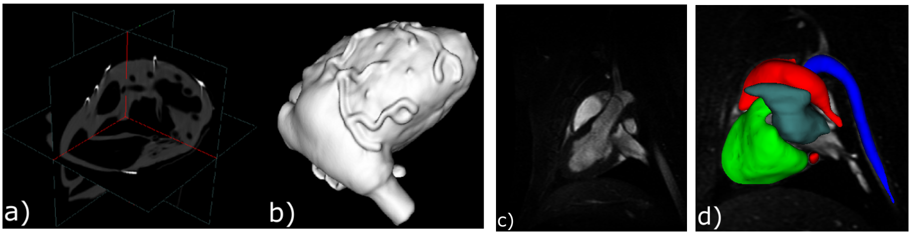

Fig. 2. a) CT image of beating heart phantom; b) Surface model of phantom extracted from CT image; c) Pre-operative cardiac MR image of porcine subject at mid-diastole; d) Heart model showing various chambers extracted from MR image

A common obstacle encountered is the extraction of fine anatomical structures (i.e. mitral or aortic valve) from low-resolution, thick-slice, clinical MR data. To address this issue, we have developed and tested a technique on human MR data that relies on fitting a high-resolution, average heart model to clinical-quality MR datasets of new subjects via non-rigid registration, leading to reasonably accurate subject-specific models. Nevertheless, for the time being, porcine cardiac models are generated via manual segmentation, as we are in the process of building a porcine heart atlas similar to that employed for humans.

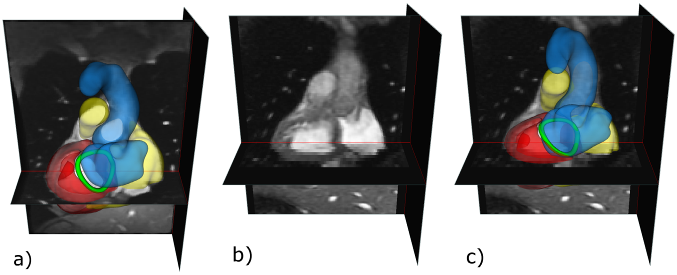

Fig. 3. a) Prior cardiac model at MD, containing segmented LV, LA/Ao, RA/RV, MVA, and AVA; b) Clinical quality subject MR image at MD; c) Clinical quality subject MR image segmented using the prior model

Ultimately, a dynamic cardiac model depicting the heart at different time points in the cardiac cycle is obtained by sequentially propagating the static model throughout the cardiac cycle with the motion estimated via non-rigid image registration [10] and rendered to portray the dynamics of the heart.

Model-to-Subject Registration. We employ a peri-operative feature-based registration technique to augment the intra-operative US images (Fig. 4a) with the pre-operative cardiac models (Fig. 4b). Easily identifiable targets in both datasets, the mitral (MVA) and aortic (AVA) valve annuli, are chosen to drive the registration. The pre-operative annuli are segmented manually from the cardiac MR image using a custom-developed spline-based segmentation tool (Fig. 4b). The intra-operative annuli are extracted from "pseudo" 3D US volumes generated by assembling 2D TEE images acquired at finite angular increments, according to their spatial and temporal time-stamps encoded by the tracking system and ECG-gating. The algorithm first aligns the centroids (translational component) and normal unit vectors (rotational component) corresponding to the homologous annuli, and ultimately refines the alignment via an iterative closest point approach, minimizing distance between homologous features.

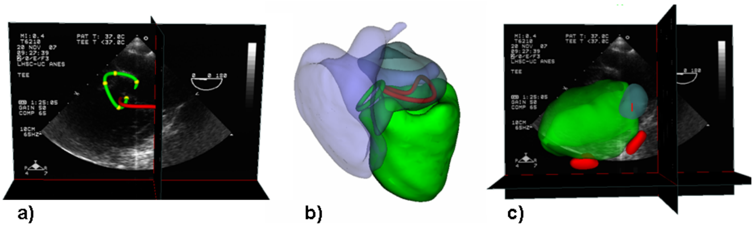

Fig. 4. a) Intra-operative US image, and b) pre-operative model, showing the MVA and AVA; c) Pre- and intra-operative datasets fused via feature-based registration

This mapping technique is suitable for cardiac interventions, as it does not significantly lengthen procedure time, the selected valvular structures are easily identifiable in both datasets, and they also ensure a good alignment of the pre- and intra-operative surgical targets. Furthermore, given the location of the features used to drive the registration, we expect good anatomical alignment in the surrounding regions, enabling us to employ this technique for a variety of image-guided intracardiac interventions.

Surgical Tool Tracking. For all off-pump interventions, the surgeon must to know the position and orientation of the instruments with respect to the intrinsic surrounding anatomy at all times during the procedure. We integrate this feature via surgical tool tracking using the NDI Aurora (Northern Digital Inc., Waterloo, Canada) magnetic tracking system. Virtual representations of the instruments, registered to their physical counterparts, are tracked in real time relative to the pre- and intra-operative anatomy within the AR environment. In addition, a reference sensor is 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.

As an example, for a MV implantation, we need virtual representations for the TEE transducer, valve-guiding tool and valve-fastening tool Fig. 5. A more

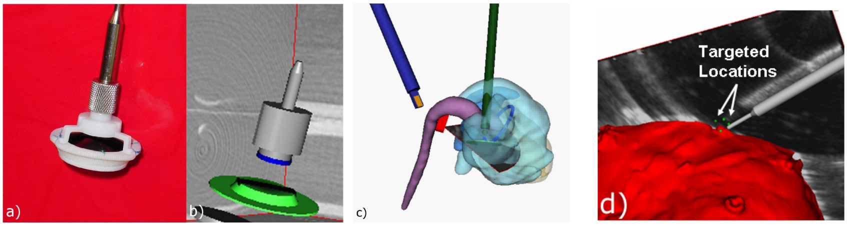

Fig. 5. a) Physical and b) virtual representation of a prosthetic mitral valve attached to the valve-guiding tool; c) AR environment specific to an *in vivo* porcine study, and d) *in vitro* beating heart phantom study

sophisticated model is required for the US probe, as it incorporates the video feed from the scanner and the image plane must be automatically adjusted to changes in rotation angle and depth as manipulated by the sonographer.

3 Assessing Therapeutic Feasibility

3.1 Endocardial Interventions in Phantoms

To assess the feasibility of surgical navigation under augmented reality-assisted guidance, we performed extensive tests *in vitro* on a beating heart phantom, mimicking left or right atrial endocardial procedures, where the surgeons would use a tracked instrument (i.e. ablation catheter) to “deliver therapy” to intracardiac targets in absence of direct vision. Moreover, we compared AR-guided targeting accuracy and procedure duration with those achieved under US image guidance alone (i.e., typical guidance modality employed for similar procedures), and endoscopic guidance. Although the latter is not a guidance option for intracardiac procedures, it nevertheless provides similar visualization to that available under direct vision, and therefore allows us to establish a positive control in terms of both accuracy and duration.

Three users conducted the *in vitro* catheter navigation on four surgical targets, whose positions were tracked simultaneously using 5 DOF magnetic tracking sensor coils. Each user attempted the targets in 4 trials (i.e., 4 consecutive target sequences, each with a different target order) under each guidance modality (endoscopic, VR-US, and 2D US image guidance). The procedure outcome was assessed according to the targeting accuracy — distance between the tip of the catheter and the surgical target at the time of contact, as well as the duration of each trial (Fig. 7).

3.2 Initiating Clinical Translation

Direct access to the cardiac chamber was achieved using the Universal Cardiac Introducer (UCI) [11]. The AR environment consisted of the pre-operative model

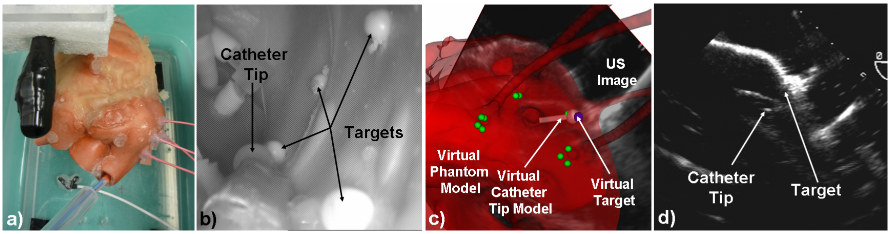

Fig. 6. Graphical representation of targeting accuracy and procedure duration achieved under endoscopic, VR-US, and 2D US image guidance, respectively. Note a significant improvement in both targeting accuracy and procedure duration under VR-US guidance with respect to 2D US image guidance.

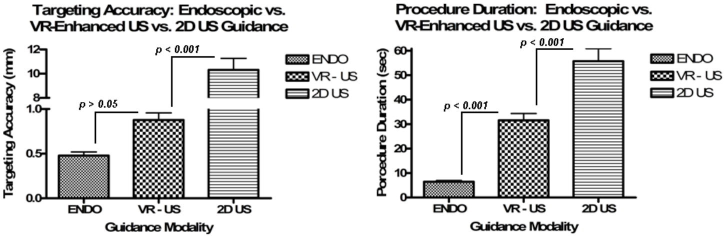

Fig. 7. Graphical representation of targeting accuracy and procedure duration achieved under endoscopic, VR-US, and 2D US image guidance, respectively. Note a significant improvement in both targeting accuracy and procedure duration under VR-US guidance with respect to 2D US image guidance.

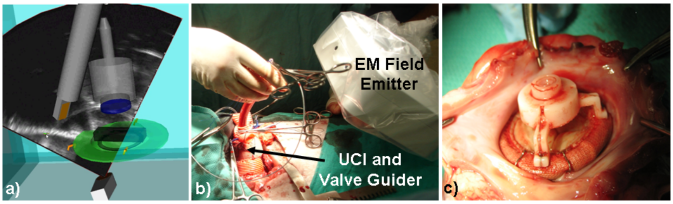

Fig. 8. a) AR environment showing virtual models of the US probe and surgical tools; b) OR setup during AR-guided interventions; c) Post-procedure assessment image

registered to the intra-procedure US, and virtual representations of the valve-guiding tool and valve-fastening tool, in this case a laparoscopic clip applier. The procedure involves the positioning and fastening of the valve onto the native mitral annulus. Both steps entail navigating the tools to the target under guidance provided by the virtual models, followed by the correct positioning and attachment of the valve via surgical clips, guided via US (Fig. 8). Intra-operative assessment using Doppler imaging confirmed a successful valve placement, also observed in the post-procedure analysis. Nevertheless, one of the applied surgical clips failed to properly secure the valve due to poor penetration into the tissue.

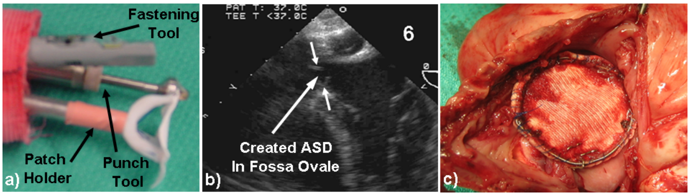

Fig. 9. a) Tools employed during the ASD creation and repair; b) 2D US image showing the septal defect; c) Post-operative image showing the successful ASD repair

The atrial septal defect (ASD) repair procedure entails similar tasks as the MV implantation, however the surgical target does not exist naturally in the porcine heart. The septal defect was therefore created by removing a circular disc of tissue from the fossa ovale under US guidance, using a "hole-punching" tool. The blood flow through the ASD was identifiable on Doppler US, and the repair patch was guided to the target under virtual reality guidance. Once on target, US imaging was used to correctly position the patch onto the created ASD and anchor it to the underlying tissue. Correct ASD repair was confirmed in the post-procedure assessment (Fig. 9b). While the VR-enhanced US guidance provided significant assistance in both navigation and positioning, this study also raised the need to improve tool design to better suit the limited intracardiac space.

4 Challenges and Lessons Learned

In spite of our recent successes, the translation from the lab to the clinic has helped us identify several roadblocks that had not posed major concerns within the *in vitro* laboratory conditions. Here we summarize some of these the issues.

One must keep in mind that cardiac IGS will always be prone to higher inaccuracies, mainly due to the high degree of rapid movement of cardiac tissue and the limitations of working in a blood filled environment. These challenges are further amplified by the difficulty of building perfect models of a subject's heart and the limited accuracy to register the model to the subject. In our work, we have studied model accuracy in predicting surgical target location [12], quantified the alignment of the pre- and intra-operative anatomy [13,14], and assessed the augmented reality-assisted targeting accuracy [15]. For the purpose of the applications of interest, our system proves clinically feasible, considering the magnetic surgical tracking accuracy on the order of 1-2 mm and the scope of the pre-operative models as aids to enhance intra-operative anatomical context.

Surgical tool design and manufacture, when subject to constraints imposed by the cardiac anatomy, interventional application, and surgical environment, is another challenge. To accommodate our needs, we built various prototypes (i.e., valve- or ASD patch-guiding tools) or adapt previous tools (i.e., laparoscopic abdominal stapler used as fixation device), embedded the MTS sensors within the tools, and tested their compatibility with the surgical environment. However, the most efficient approach would be to involve a medical device manufacturer in the project and have them build tools that will help us achieve the millimetre accurcy goal for this project.

Over the years, surgeons have become used to "standard views" of human anatomy. However, minimal invasiveness restricts both visual and surgical access, and moreover, in off-pump intracardiac interventions, surgeons cannot "see" what they do; rather, the AR guidance platform **is** their eyes. Hence, we have learned that it is often best to maintain intuitive guidance by making use of displays most familiar to surgeons. The optimal approach is to make the new look as much like the old, and instead of overwhelming them with a lot of new technology at once, rather give them the time to get accustomed to the new environments, and let them tell you how impressed they are. For the time being, our surgical team has reported great comfort using both overhead monitors and head-mounted display (HMD) units for visualization, which allow the surgeons to directly "navigate" within a virtual volume [16].

5 Conclusions

We have briefly described several IGS components developed and validated in our laboratory and outlined the path to translate traditional cardiac surgery into an AR environment in a clinical setting. Some of the lessons learned while paving the road to the clinic have proved to be rather harsh and we still expect several other surprises down the road, given the increased complexity of the procedures attempted. Nevertheless, new image guidance tools are being developed continuously, a new cohort of surgeons is recruited annually, so is not unreasonable to expect that operating rooms of the future will be routinely equipped with image-guidance systems such as the system described here.

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