Targeting Accuracy under Model-to-Subject Misalignments in Model-Guided Cardiac Surgery

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Abstract. In image-guided interventions, anatomical models of organs are often generated from pre-operative images and further employed in planning and guiding therapeutic procedures. However, the accuracy of these models, along with their registration to the subject are crucial for successful therapy delivery. These factors are amplified when manipulating soft tissue undergoing large deformations, such as the heart. When used in guiding beating-heart procedures, pre-operative models may not be sufficient for guidance and they are often complemented with real-time, intra-operative cardiac imaging. Here we demonstrate via *in vitro* endocardial "therapy" that ultrasound-enhanced model-guided navigation provides sufficient guidance to preserve a clinically-desired targeting accuracy of under 3 mm independently of the model-to-subject misregistrations. These results emphasize the direct benefit of integrating real-time imaging within intra-operative visualization environments considering that model-to-subject misalignments are often encountered clinically.

1 Introduction

The development of minimally invasive alternatives to conventional cardiac interventions are under active investigation to reduce trauma and recovery time [1,2,3]. To accelerate the progress toward the ultimate, least invasive treatment approach — beating heart intracardiac therapy, robust intra-operative visualization is crucial. These environments need to faithfully represent the surgical field, assist the surgeon with correctly identifying the targets to be treated, and guide the clinician to accurately navigate the instruments to the correct location [4].

Registration is a critical component of image-guided surgery, as it enables accurate "blending" of all disparate pieces of information (pre- and intra-operative data, the patient, and surgical tools) into a common framework. Due to their mathematical complexity and computational inefficiency, some registration algorithms may not be suitable for use in time-critical interventional applications in the operating room (OR). Instead, fast, simple, and OR-friendly registration techniques are employed, often at the expense of misalignments (Fig. 1) present in the visualization environment [5].

G.-Z. Yang et al. (Eds.): MICCAI 2009, Part I, LNCS 5761, pp. 361–368, 2009.

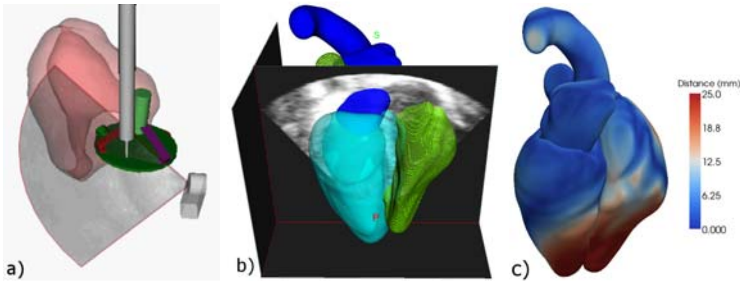

Fig. 1. a) AR environment used to guide an *in vivo* off-pump procedure in a porcine subject, showing pre-operatively generated anatomical model, tracked 2D US image, and virtual tool models; b) Pre-operative model registered to intra-operative US image, and c) error map showing misalignments across the surface model

Recently, Ma *et al.* [6] proposed a feature-based registration technique that relies on the alignment of the left ventricular surface and centerline of the descending aorta to fuse pre- and intra-operative data using a weighted iterative closest point (ICP) registration approach; similarly, we have shown clinically-suitable fusion of pre-operative models and intra-operative US data via aligning reconstructed valve annuli *et al.* [7]. While the features driving the registration are different, both techniques provide comparable anatomical alignment (4-5 mm) of the pre- and intra-operative data. However, although clinically favourable, the achieved alignment may not be suitable for model-guided therapy, without "refined guidance" provided via real-time intra-operative imaging.

We employ an augmented reality (AR)-assisted image guidance platform [8] that integrates real-time trans-esophageal echocardiography (TEE), enhanced with pre-operative heart models, and surgical instrument localization. This platform allows clinicians to explore the intracardiac environment using the pre-operative models as guides for tool navigation [9], but therapeutic success may be subject to the model-to-subject registration accuracy.

The goal of this work is to mimic *in vitro* model-to-subject misregistrations similar to those encountered in cardiac applications and show how our guidance platform provides sufficient navigation information to maintain accurate targeting, in spite of slight misregistrations. This work demonstrates the value of pre-operative models as a means of quickly navigating to the neighbourhood of the target, with real-time US used to refine the targeting operation.

2 Materials and Methods

We mimicked *in vitro* endocardial ablation procedures in a beating heart phantom. To demonstrate the robustness of our surgical platform, we then altered the position and orientation of the pre-operative phantom model in the visualization environment with respect to its real-world counterpart. This procedure enabled us to simulate misalignments similar to those observed in clinical applications and quantify the success of "therapy delivery" to specific endocardial targets.

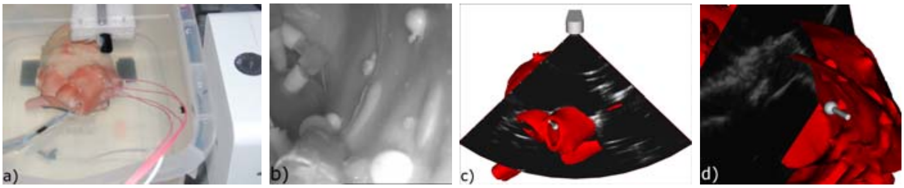

Fig. 2. a) Beating heart phantom setup, with catheter and US probe; b) Endoscopic view of the endocardial surgical targets; c) Virtual surgical field (phantom model, tracked 2D US probe and fan), accompanied by a cut-away endocardial view showing targets and virtual catheter tip

2.1 Experimental Design

The study was performed on a pneumatically-actuated beating heart phantom (The Chamberlain Group, Great Barrington, MA, USA). Ten CT-visible fiducials were attached onto the epicardial surface of the phantom to assist with the model-to-phantom registration. Four surgical targets (3.2 mm Teflon spheres) were implanted into the endocardial surface, mimicking right atrial pathology. Their position was tracked throughout the cardiac cycle using 5 degree-of-freedom NDI Aurora magnetic sensors embedded within each sphere. Therapy delivery consisted of users navigating the tip of a tracked catheter to each target (Fig. 2).

2.2 Image-Guidance Platform

Model-guided Visualization. In a typical procedure, a pre-operative image or model of the patient's heart featuring the surgical targets is registered to the patient in the OR. To mimic the clinical work flow, we first acquired a gated (60 bpm) cine CT dataset (0.48 x 0.48 x 1.25 mm^3) that depicts the phantom at 20 phases over the cardiac cycle. Using segmentation tools available in the Vascular Modeling ToolKit (http://www.vmtk.org), we reconstructed virtual surface models at each cardiac phase and rendered them in "cine" mode for dynamic visualization (Fig. 2).

Real-time Imaging. TEE is extensively used in interventional guidance thanks to its excellent real-time capabilities and OR compatibility. A distinct feature of our surgical platform consists of the acquisition of *tracked* 2D TEE images in real-time, enabling their display within anatomical context provided by the virtual model and relative to the tracked surgical tools. While most of our work is based on tracked TEE for intra-procedural imaging, similar results can be achieved using intracardiac or laparoscopic US imaging as shown in [10]. Here the TEE transducer is tracked using a 6 DOF magnetic sensor attached to the probe and calibrated using a Z-string technique [11].

Virtual-to-Real World Registration. The key to building accurate navigation environments lies within the registration of all components into a common

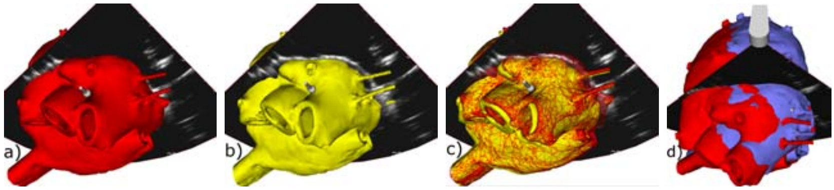

Fig. 3. a) Well-registered and (b) misregistered phantom model w.r.t. its physical counterpart (note epicardial contour in US image); c) Superimposed well-aligned (red wireframe) and translated (yellow surface) models, and d) Superimposed well-registered (red) and rotated (blue) model, mimicking clinically encountered misalignments

framework. The virtual models of surgical tools, US transducer and echo images are intrinsically registered to the tracking coordinate system and to each other via their respective "tool-to-sensor" calibration transforms.

The challenging step is registering the patient (in this case the heart phantom), initially in tracking coordinate system, to that of the pre-operative model. In the clinic this step is achieved via either landmark- or feature-based registration, and resulting misalignments further propagate and impact targeting accuracy. We used a point-based registration algorithm involving epicardial fiducial markers to register the virtual model to the physical phantom. Temporal alignment was achieved by synchronizing the "model heart rate" with the ECG signal driving the actuator, resulting in nearly real-time visualization.

Inducing "Model-to-Subject" Misregistrations. Most image-guided cardiac procedures, including those performed on the open heart, suffer from misalignments between the pre- and intra-operative data. Surgical target locations, although accurately labeled pre-operatively, may not align with their intra-operative location, and may even show as situated outside the cardiac chamber, in which case careless navigation could lead to severe outcomes (Fig. 3).

We simulated two misalignment scenarios often encountered in the OR. The former mimics a translational misalignment, similar to that observed after the pericardial sac is opened to access the heart; the latter mimics a rotational misalignment, arising due to a slightly different orientation of the heart between imaging and intervention. For this study, the phantom model was mapped to its "new" location using the misalignment transforms explored above. Hence, the position and orientation of all tracked tools and US probe remained the same with respect to one another and to the physical phantom, but their location with respect to the model displayed in the visualization environment was changed.

2.3 Surgical Guidance

To evaluate the effect of model-to-subject misregistration on targeting accuracy, we conducted several experiments where users relied solely on model-guided visualization or VR-enhanced US guidance for therapy delivery, under both well-aligned, as well as misaligned conditions. In a previous study, the same

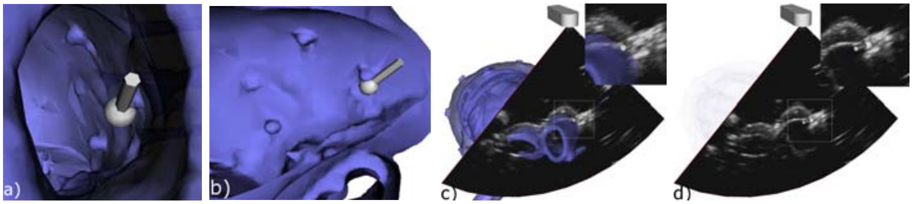

Fig. 4. US enhanced model-assisted guidance work flow: a) initial navigation via virtual anatomy and tool model using two orthogonal views (b), followed by US model enhancement (c), and final target identification and tool tip positioning performed under real-time US guidance (d)

experiment was performed under US image guidance alone to illustrate the limitations of 2D imaging regarding tool navigation. Moreover, to establish a baseline (i.e., positive control) with respect to targeting accuracy, therapy delivery was also conducted under endoscopic guidance. While not suitable for visualization in blood-filled cavities, endoscopic guidance closely mimics a direct vision procedure and its outcomes.

Users were blinded to whether or not the model was properly registered to the phantom, so relying on the model alone might not have led to accurate targeting. Therefore, they adopted a "therapy delivery work flow" where the initial tool to target navigation was performed under model-assisted guidance. Once on target, the display of the model was dimmed, while the tracked 2D US image was emphasized, allowing users to identify the true target location and refine their tool location based on the virtual tool representation and the real-time US image (Fig. 4).

3 Evaluation and Results

Three novice users conducted the *in vitro* catheter navigation on four surgical targets, whose positions were tracked simultaneously. The four targets were approached in sequence, and the order of the targets was arbitrarily generated for each sequence. Each user attempted to localize the targets in 4 trials under virtual model guidance alone (VR), as well as US-enhanced model guidance (VR-US), with no prior knowledge of the model-to-phantom registration. In a previous study, the same three users performed the similar task under endoscopic and US image guidance alone. Prior to acquiring the measurements, each user was allowed a short training period to become accustomed to the "surgical navigation" technique. The procedure outcome was assessed according to targeting accuracy — the distance between catheter tip and surgical target when in contact (**Table 1**).

We performed an analysis of variance (ANOVA) followed by a Tukey's post-hoc test (GraphPad Prism 4.0) to identify significant differences in procedure accuracy with respect to the guidance modality employed and to evaluate the effect of the model-to-phantom registration on targeting accuracy.

Table 1. RMS targeting accuracy (mm) w.r.t. guidance modality and model alignment

Guidance	Registered Model				Translated Model		Rotated Model	
Modality	ENDO	US	VR	VR-US	VR	VR-US	VR	VR-US
Global	0.5	14.8	0.9	0.7	2.9	1.1	3.4	1.4
Target 1	0.4	13.4	0.8	0.8	3.2	0.9	3.1	1.1
Target 2	0.3	14.8	1.0	0.8	2.4	1.2	3.2	1.7
Target 3	0.5	20.3	0.7	0.7	2.9	1.4	3.4	1.6
Target 4	0.6	9.4	1.1	0.5	3.1	0.8	3.7	0.9

4 Discussion

Our study following accurate model-to-phantom registration [12] showed that both the model-assisted (VR) and US-enhanced model-assisted (VR-US) guidance led to significantly more accurate targeting ($p < 0.001$) than 2D US imaging alone; moreover, no significant difference was observed between the endoscopic and the two model-assisted guidance modalities ($p > 0.05$) (Fig. 5). Model-assisted guidance also reduced the "procedure" time in half [12].

Next, we analyzed the effect of model-to-subject registration on the guidance modality employed. The chosen "misalignment transforms" induced a surgical target "shift" of 3-5 mm depending on their locations. Following model-assisted guidance, we observed a significant decrease in targeting accuracy ($p < 0.001$) compared to that recorded under well-aligned conditions (Fig. 5). On the other hand, while targeting accuracy was inadequate, targeting precision was maintained; by mapping the "targeted sites" using the inverse of the misalignment transforms, we were able to reconstruct the "true" locations of the surgical targets. Hence, these navigation errors were induced by the misleading environment.

However, once model-assisted guidance was augmented with real-time US, we observed a significant retrieval of targeting accuracy. For the translational misalignment case, targeting accuracy achieved under model-assisted guidance alone dropped to an overall 3 mm RMS; however, it was restored to an overall 1.1

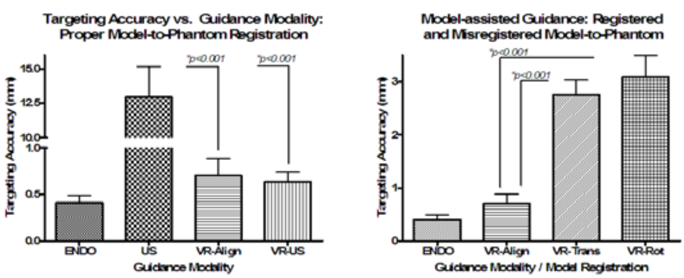

Fig. 5. Superior targeting accuracy is achieved under AR-assisted vs. US imaging alone; however, accuracy of *model-only guidance* (VR) is greatly reduced under misalignments

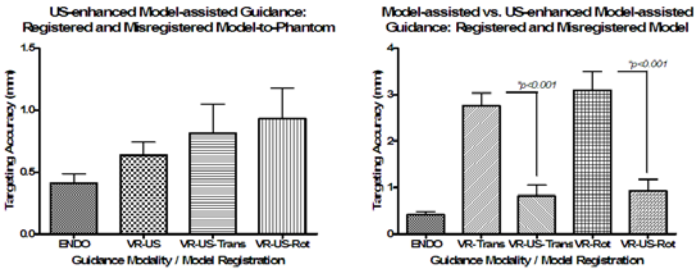

Fig. 6. US-enhanced model-assisted guidance (VR-US) shows consistent targeting accuracy independently of model-to-subject registration. Note the significantly improved accuracy with US-enhanced model-assisted (VR-US) guidance under misregistration.

mm RMS error via US-enhanced guidance ($p < 0.001$). Similarly, model-assisted guidance accuracy was significantly improved with the addition of US imaging, from 3.1 mm targeting error to 1.4 mm RMS (Fig. 5). Moreover, virtual reality-enhanced US guidance maintained a high level of accuracy regardless of the model-to-subject registration ($p < 0.001$) (Fig. 6).

For qualitative evaluation, we recorded "targeting maps" after each "therapy delivery" session. A compact distribution of targeted sites was observed under endoscopic guidance, and maintained under both model-assisted and US-enhanced model-assisted guidance. The main drawbacks of US image guidance arose due to limited information provided for navigation; the lack of context and poor instrument perception, 2D US alone cannot adequately portray the 3D surgical environment. US image guidance alone hampers the navigation step, leading to large targeting errors, while model-assisted guidance alone hampers the positioning step, leading to precise, but insufficiently accurate targeting.

5 Conclusions

This study is key for evaluating our AR-assisted surgical guidance platform. We have shown that despite slight misalignments between the virtual model and the subject, real-time US does provide sufficient information to identify the true target location and compensate for the navigation errors, ultimately enabling consistent targeting accuracy on the order of 1-1.5 mm.

Acknowledgments. The authors thank Mathew Carias, Carling Cheung, Danielle Pace, Petar Seslija and Dr. Aaron So for help with data acquisition. In addition, we acknowledge funding for this work provided by the following Canadian agencies: NSERC, CIHR, HSFC, ORDCF, OIT and CFI.

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