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Towards fluoro-free interventions: Using radial intracardiac ultrasound for vascular navigation

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Abstract:	Transcatheter cardio-vascular interventions have the advantage of patient safety, reduced surgery time, and minimal trauma to the patient's body. Transcathether interventions, which are performed percutaneously, suffer from the lack of direct line-of-sight with the surgical tools and the patient anatomy. Therefore, such interventional procedures rely heavily on image guidance for navigating towards and delivering therapy at the target site. Vascular navigation via the inferior vena cava (IVC), from the groin to the heart, is an imperative part of most transcatheter cardiovascular interventions such as valve repair surgeries and ablation therapy. Traditionally, the IVC is navigated using fluoroscopic techniques such as angiography or CT venography. These X-ray based techniques can have detrimental effects on the patient as well as the surgical team, causing increased radiation exposure, increased risk of cancer, fetal defects, eye cataracts. The use of heavy lead apron has also been reported to cause back pain and spine issues thus leading to interventionalist's disc disease. We propose the use of a catheter-based ultrasound augmented with electromagnetic (EM) tracking technology to generate a vascular roadmap in real-time and perform navigation without harmful radiation. In this pilot study, we use intracardiac echocardiography (ICE) and tracking technology to reconstruct a vessel from a phantom in a 3D virtual space. This paper presents a pilot phantom study on ICE-based vessel reconstruction and demonstrates how the proposed ultrasound-based navigation will appear in a virtual space, by navigating a tracked guidewire within the vessels in the phantom without any radiation-based imaging. The geometric accuracy is assessed using a CT scan of the phantom, with a Dice coefficient of 0.79. The average distance between the surface of the two models comes out to be 1.7 ± 1.12mm.
Suggested Reviewers:	
Opposed Reviewers:	

To,
Christy K. Holland
Editor-in-Chief,
Ultrasound in Medicine and Biology (UMB)

Date: 20th August 2021

Subject: Cover Letter for UMB submission – "Towards fluoro-free interventions: Using radial intracardiac ultrasound for vascular navigation"

Dear Dr. Holland,

We are pleased to submit our research to the UMB journal. We state that this manuscript is of original contribution and has not and will not be submitted elsewhere for publication. The contribution from individual authors is stated as the following:

1. Hareem Nisar – primary researcher – design and execution of the study, performing all the experiments, most of the code generation, and writing the journal article.
2. Leah Groves – secondary researcher – part of the code generation, writing part of the paper, and editing the manuscript.
3. Leandro Cardarelli-Leite – clinical advisor – providing clinical motivation and regular insights towards the project, paper design, and editing.
4. Terry M. Peters – senior advisor – project supervision, grant holder, paper design and editing
5. Elvis C.S. Chen – senior advisor – project supervision, resource management, paper design, and editing.

All authors have individually approved the submission of this manuscript to UMB. Thank you for considering our submission.

In case of any query, please reach out to us at hnisar3@uwo.ca or chene@robarts.ca.

Best regards,

Hareem Nisar

Towards fluoro-free interventions: Using radial intracardiac ultrasound for vascular navigation

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Abstract

Transcatheter cardio-vascular interventions have the advantage of patient safety, reduced surgery time, and minimal trauma to the patient's body. Transcathether interventions, which are performed percutaneously are limited by the lack of direct line-of-sight with the surgical tools and the patient anatomy. Therefore, such interventional procedures rely heavily on image guidance for navigating towards and delivering therapy at the target site. Vascular navigation via the inferior vena cava (IVC), from the groin to the heart, is an imperative part of most transcatheter cardiovascular interventions including heart valve repair surgeries and ablation therapy. Traditionally, the IVC is navigated using fluoroscopic techniques such as angiography or CT venography. These X-ray based techniques can have detrimental effects on the patient as well as the surgical team, causing increased radiation exposure, leading to risk of cancer, fetal defects, and eye cataracts. The use

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of heavy lead apron has also been reported to cause back pain and spine issues thus leading to interventionalist's disc disease. We propose the use of a catheter-based ultrasound augmented with electromagnetic (EM) tracking technology to generate a vascular roadmap in real-time and perform navigation without harmful radiation. In this pilot study, we use spatially-tracked intracardiac echocardiography (ICE) to reconstruct a vessel from a phantom in a 3D virtual environment. We demonstrate how the proposed ultrasound-based navigation will appear in a virtual environment, by navigating a tracked guidewire within the vessels in the phantom without any radiation-based imaging. The geometric accuracy is assessed using a CT scan of the phantom, with a Dice coefficient of 0.79. The average distance between the surface of the two models comes out to be 1.7 ± 1.12 mm.
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Introduction

Advances in medical imaging, combined with miniaturized and flexible surgical tools, have allowed surgical procedures to be performed percutaneously using transcatheter-based approaches. These minimally invasive approaches have increased patient safety, decreased procedure time, and lowered complication rates (Jahangiri et al., 2019). Catheter-directed therapies inherently prohibits the direct line-of-sight with the anatomy and the tools. Interventionalists rely heavily on image-guidance to navigate and position their tools to deliver therapy at the target region. Common imaging modalities used for transcatheter-based interventions include X-ray fluoroscopy, computed tomography (CT), magnetic resonance imaging (MRI), and intravascular (IVUS), intracardiac (ICE) or transesophageal (TEE) ultrasound (US).

Fluoroscopy is commonly used for minimally invasive procedures as it provides real-time, high contrast vascular images, by means of X-ray imaging with contrast enhancement. The radiation exposure produced by X-rays can be harmful to the patient, clinical staff, and medical trainees, even when used in conjunction with various shielding techniques (Theocharopoulos et al., 2006; Christopoulos et al., 2016). The use of heavy shielding aprons may have detrimental effects on the physical health of the interventional team causing "interventionalist's disc disease" (Ross et al., 1997) which includes back and neck pain (Dixon et al., 2017), cervical disc herniation, and other spinal and musculoskeletal issues (Goldstein et al., 2004), as well as the possibility of lead poisoning (Katsari et al., 2020). Interventional cardiologists and radiologists have reported developing eye cataracts (Jacob et al., 2013), increased

risk of cancer (Roguin et al., 2013), and increased risk of fetal congenital defects (Limacher et al., 1998). The use of contrast agents to compensate for the lack of soft-tissue visualization in X-rays can induce complications for patients with renal impairments and allergic reactions (Davenport et al., 2015).

Due to its high resolution and large field of view, pre-operative CT is a standard of care for vascular mapping and assessment of intravascular pathology (Murphy et al., 2018). However, CT imaging is typically used for diagnostic and pre-surgical planning, and is limited in it's use for real-time surgical navigation. CT is also based on ionizing radiation and carries the same risks previously described for fluoroscopy. Furthermore, the surgery cannot be performed with the patient within the CT bore. In transcatheter procedures, there is an unmet need for safe, reliable, radiation-free and real-time image-guidance during vascular navigation.

In efforts of minimizing the radiation exposure in Cath labs, near-zero fluoro methods and no-fluoro surgical workflows have also been proposed in the literature (Stec et al., 2014; Zhang et al., 2020) to guide the catheters during an ablation procedure and perform transseptal puncture using ICE. Alternative imaging modalities such as MR, and US are also considered. Vascular navigation is fundamental to transcatheter cardiac interventions such as transcatheter aortic valve implantation (TAVI), caval-valve implantation, and mitral and tricuspid valve annuloplasty, repair and replacement surgeries (Prendergast et al., 2019). Accurate representation of the vessel geometry is not only important for navigation towards the target site, but also for delivering the optimal therapy (Murphy et al., 2017; Shammas et al.,

2019). Procedures such as angioplasty, stent placement, IVC filtration all rely on vascular imaging to locate the pathological vessel region, select an appropriately sized device, and deploy the balloon or stent correctly.

Catheter-based US technologies such as intravascular US (IVUS) and intracardiac echo (ICE) are already indispensable components of Cardiac Catheterization labs (Cath Lab), assisting in the assessment of the disease and device placement. The recent introduction of optical US (OpUS) technology also shows the great potential for the use of catheter-based US for cardiovascular interventions (Little et al., 2020). US offers a radiation-free alternative for real-time image guidance. When combined with EM tracking technology, it offers the potential for a large-scale 3D US volume reconstruction, visualization of anatomy, as well as real-time tool tracking. For most transcatheter interventions, there are two surgical phases - navigation of tools towards the target site and positioning of tools to deliver the treatment. In the case of cardiac interventions, vascular navigation is an imperative prerequisite. Either transfemoral, transradial or transjugular access is required to guide the catheters towards the heart. Inferior vena cava (IVC) navigation, from the groin to the chest, is one of the most common techniques in cardiology and is traditionally guided by fluoroscopy. In this paper, the targeted clinical application is the IVC navigation performed during transcatheter cardiovascular interventions.

We propose the use of tracked US as an alternative to CT-based vascular mapping and fluoro-guided tool navigation. Instead of using radiation-based imaging to navigate the tools, we propose the following surgical workflow: Prior to the intervention, a tracked, catheter-based US probe (such as ICE,

IVUS, or OpUS) scans the desired vasculature and a virtual 3D roadmap is reconstructed. This vascular path can then be easily traversed by a tracked tool or guidewire. This workflow eliminates radiation exposure and the use of heavy lead equipment. Such a system can also be used to make measurements of the vessel anatomy and intraluminal buildup. Ultrasound catheters including ICE and IVUS, as well as EM tracking technology are already an indispensable part of a Cath Lab and are used in electrophysiology procedures. The proposed ultrasound-based workflow has several advantages over the conventional fluoroscopic techniques. Apart from the lack of radiation, and heavy lead shielding equipment, an US-based navigation system offers full 3D visualization of anatomy, and provides more information to the clinician. Furthermore, the use of EM tracking technology allows for tracked tools and catheters which can result in an engaged and informative experience for the clinicians. These features greatly reduce the cognitive load faced by the interventionalists and will potentially result in enhanced procedural outcome as well.

In this study, we utilized a Foresight ICE system – an intracardiac ultrasound probe which involves a single-element transducer, spinning on its axis and tilted at a user-specified angle. As a result, the ultrasound image produced is a 2D conical surface image lying in 3D space. One of the biggest advantages of using this probe for navigation is the 'Forward-viewing' feature which allows the clinicians to watch where they are going as they traverse the vessels, thus improving their experience and adding a layer of procedural safety. The use of ICE probe is not limited to navigation. For transcatheter cardiac interventions, the ultrasound can further facilitate the delivery of

therapy or treatment. This study is geared towards the navigation of inferior vena cava (IVC), it also has the potential to be applied to the navigation of other vessels as well. IVC has many tributaries, but they need not to be navigated for cardiac procedures. The geometry of IVC is also comparatively simpler than its tributaries like hepatic veins. Since the IVC passes through the entire length of the abdomen, it's surrounding tissues and organs vary along the length. Thus, the appearance of the IVC in the ultrasound varies as well. All these physical and echogenic attributes of IVC are difficult to capture in one phantom. Therefore, for this first, phantom study we are demonstrating the concept on an ultrasound-realistic phantom representing the infrarenal portion of the IVC. The goal is to reconstruct a vascular roadmap without any radiations, safely navigate the guidewire through the vessel, and visualize the guiding catheters as they ascend towards the heart.

This paper presents a pilot phantom study as a proof of concept to demonstrate the idea and feasibility of an US-based vascular navigation system for transcatheter interventions. A vascular phantom was scanned and reconstructed using a forward-looking radial ICE probe and EM tracking technology. The method details, open-source implementation, and phantom images are available online for reproducibility (`https://github.com/hareem-nisar/VascularNavigation`). The US-generated vessel model is validated against a CT-scan of the vessel phantom. For a visual validation and concept demonstration of real-time guidance, we also demonstrate navigation of a tracked guide-wire in a vascular phantom using the proposed US-based approach.

Materials and Methods

Data Acquisition

A polyvinyl alcohol cryogel (PVA-C) vascular phantom was manufactured to imitate the infra-renal portion of the IVC (Nisar et al., 2020). The phantom generated realistic US imaging when scanned by an intravascular (IVUS) or intracardiac (ICE) US, thus displaying a vessel-mimicking layer, blood-mimicking fluid in the lumen, and a surrounding tissue-mimicking layer. In this study, a 10 Fr, forward-looking, Foresight™(Conavi Medical Inc., North York, ON, Canada) ICE catheter was used to image the phantom. This probe generates 3D conical surface images, where the angle of the cone is user adjustable. The conical images are projected on a conventional monitor screen as viewed from the apex of the cone and displayed as a circular image. A digital frame-grabber (DVI2USB 3.0, Epiphan Video, Ottawa, ON, Canada) was used to capture the projected ICE images, and the cone-angle information from the console. For US tracking, the ICE probe was rigidly instrumented with a 6DoF pose sensor (Aurora, NDI, Waterloo, ON, Canada) and spatially calibrated using a point-to-line Procrustean approach (Chen et al., 2016; Nisar et al., 2019).

The vessel phantom was placed in a large water-bath at room-temperature (Fig. 1). The main vessel of the phantom was scanned using the tracked ICE probe at an imaging depth of 80 mm, imaging angle of 67 ° and 12 MHz frequency. Due to some hardware constraints in our set-up, we were only able to scan the central vessel of the phantom and not the branches (details in Discussion section). US images were acquired in real-time using screen-capture. The imaging and tracking data were then processed to reconstruct

the surface representation of the vessel from the phantom. The data acquisition, vascular roadmap generation, and the user interface for navigation were all implemented as an open-source software using 3D Slicer (Fedorov et al., 2012). The steps involved in the automatic generation of the 3D vascular roadmap include pre-processing to remove image artifacts, lumen segmentation from 2D images and reconstruction of the vessel based on the segmentations and tracking information.

Pre-processing

The acquired screen-captures were cropped to remove any information outside of the US image. The bright reflections in the middle of the cropped US image represent an artifact inherent to the ICE probe (Fig. 2a). This artifact was minimized by using optimal display settings (third level 'wand' function) on the console, and later masking the central bright pixels in the image in our software. The time-gain compensation settings on the console were used to suppress the reflections from the phantom boundary and the container walls. A noise removing filter called the curve flow filter was applied to images to eliminate the interference from by the EM tracker (Fig. 2a) while preserving the contours of the vessel boundary. This was a necessary step prior to performing image processing for lumen segmentation.

Lumen Segmentation

Distinct from imaging using hand-held percutaneous US transducer, the shape of the vessel wall can vary significantly for catheter-based US. Since the US catheters travel through the vasculature adhering close to the vessel wall, the wall does not always appear as a closed circle in the case of radial IVUS

and ICE imaging. The first few millimeters of ICE imaging are corrupted by a ring artifact inherent to the radial ICE probe (Fig. 2a). As such, when the ICE catheter is clinging to the vessel wall, the reflection is interrupted close to the center of the image (Fig. 2a) and the vessel boundary appears C-shaped. Therefore, in this study, an edge-based approach was used to segment the vessel lumen from the ICE images, minimizing the error/leakages caused by a discontinuous vessel boundary. A statistics-based active contour algorithm was applied (Gao et al., 2010). This algorithm grows the boundaries of an initial seed based on the characteristics of the underlying image intensities, and can be manipulated by the parameters 'intensity homogeneity' (set to 0.8) and 'boundary smoothness' (set to 1) to maintain the roundness of the contour and minimize leakages based on intensity.

The performance of the segmentation algorithm is highly dependent on the size and placement of the initial seed. Therefore, for the algorithm to be effective, it is necessary to have an initial seed, closely fitted to and completely encapsulated and centered within the vessel lumen (Gao et al., 2010). The Hough transform was used to approximate the initial seed by fitting a circle to the lumen (Fig. 2b) (Parameters values: Hough Gradient, dp =1, min_dist=100, param1=95, param2=20). Gaussian blur was applied prior to the Hough transform to avoid over-detection of circles. To ensure that the seed does not overlap with the vessel boundary, the fitted circle was iteratively decreased in radius until there were no bright reflections in the underlying image. A hundred and eighty image frames were processed and 2D lumen segmentations were acquired for each image.

Vessel Reconstruction

The Foresight™ICE probe generates forward-looking conical surface images. The images acquired by this device, and subsequently the lumen segmentation, were a version of the true US data projected onto a 2D disk. 2D lumen segmentations were subjected to 3D conversion to reconstruct true, conical segmentations (Fig. 2c) using the radius and imaging angle information, available through the console. This reconstruction is governed by the equation:

$$\begin{bmatrix} x_{3D} \\ y_{3D} \\ z_{3D} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -o_x \\ 0 & 1 & -o_y \\ 0 & 0 & \left\|(x_{2D}), y_{2D})\right\| \cdot tan(90-\phi) \end{bmatrix} \begin{bmatrix} x_{2D} \\ y_{2D} \\ 1 \end{bmatrix} \quad (1)$$

where (o_x, o_y) represents the center of the planar image or the apex of the conical image, and ϕ represents the imaging angle of the cone-shaped image. Each segmentation was positioned and scaled to its correct shape and location in 3D space by applying US probe calibration and tracking information, producing a skeleton of the vessel (Fig. 3a). The vessel skeleton was then processed to form a closed 3D surface representation using binary morphological closing, with an annulus kernel of size $[60, 60]$ to fill the gaps between consecutive segments. For final smoothing of the reconstructed vessel, a Gaussian blur with a standard deviation of 3 was applied. The result represents the 3D model of the vessel scanned from our phantom (Fig. 3b), spatially present in the EM tracker's coordinate system.

Validation

As described previously, vascular navigation is currently achieved using fluoroscopy or CT mapping. The vessel phantom was imaged using US, and the vessel was reconstructed and compared with X-ray and CT. Geometric accuracy of the US reconstructed vessel model was validated against the vessel segmented from the CT scan of the same phantom. The absolute surface-to-surface distance between the two models were computed after a rigid registration (Besl and McKay, 1992). For vascular navigation, one of the clinically relevant goals is to know the overall alignment of the vessels in space. To evaluate the spatial alignment, we used DICE metrics which compares the spatial overlap between the reconstructed and CT vessel after CT-US registration was performed. False positive spatial region in the reconstructed US vessel is also an important metric and must be minimal to avoid the misrepresentation of the vessel. For many vascular procedures, the clinical objective is to avoid puncturing the vessels. In such cases, the boundary accuracy becomes important as well as the false positive regions. To evaluate the contours of the reconstructed vessel, we calculated the Hausdorff distance (HD) metrics (Taha and Hanbury, 2015). Volumetric analysis was not performed as volume-based metrics are invariant of segmentation shape and boundary and thus can be misleading. As a visual validation, we demonstrate what US-based navigation may look like. A tracked, straight-tip guidewire(Piazza et al., 2020), augmented with a 5DOF EM sensor, was maneuvered to navigate the vessels in the phantom.

Results

The absolute distance between the US reconstrcuted vessel and the registered CT segmenetd vessel was computed and presented as a heatmap on the vessel surface in Fig. 3c. The average distance between the surface of the two models comes out to be 1.7 ± 1.12 mm. A maximum error of 5.86 mm between the two surface models was observed. The spatial overlap between the registered US and CT models was evaluated using the Dice coefficient, sensitivity and specificity measures using:

$$Dice = \frac{TP\ overlap\ between\ CT\ and\ US\ vessels}{(num\ voxels\ CT vessel) * (num\ voxels\ US vessel)} \quad (2)$$

$$Sensitivity = \frac{TP}{TP + FN} \quad (3)$$

$$Specificity = \frac{TN}{TN + FP} \quad (4)$$

where TP, TN, FP and FN represent the true positive, true negative, fasle positive and false negative spatial overlap between the US and CT segmented vessels respectively.

The spatial distance between the two model boundaries was evaluated using the Hausdorff distance (HD). The geometric accuracy results are reported in Table 1. Comparison showed that the US model had 12.93 % false negative and 6.60 % false positive spatial overlap.

The x-ray imaging of our phantom, along with a guidewire, is represented in Fig. 4a. In comparison, we can also achieve tool guidance using an US-guided vascular navigation system. Fig. 4b shows how the US reconstructed vessel looks like in 3D space. Virtual representation of a tracked guidewire can be seen in context, as it navigates the phantom vessel.

Discussion

In this study, we present an vascular reconstruction-based surgical navigation system, which provides a safe and radiation-free method for guiding tools for X procedure. An EM-tracked ICE US probe was used to reconstruct the vascular path in a phantom, such that it can be visualized in a common coordinate system with a tracked guidewire for vessel navigation. The results indicate that the average error in terms of HD is 1.7 mm, with a 3.16 mm confidence interval, which is a clinically acceptable value (Linte et al., 2010). During navigation, it is important to identify the vessel boundary and the regions outside the vessel lumen so as to not puncture or damage the vessel wall. Our results indicate that only 6.60 % region lies outside the ground truth provided by the CT scan of the phantom. This over-segmentation is due to the leakages through the discontinuous wall boundary in some of the images when the ultrasound probe is clinging to the vessel wall. The accuracy of the navigation system can further be improved by improving the segmentation and tracking accuracy as discussed below.

The resulting error is a combination of many different errors in the system, such as EM tracking inaccuracies, propagation of calibration errors, US probe hardware constraints, registration errors, and relative motion of the phantom if any. One of the major limitations of our study is defined by the sensorizing the US probe and its calibration accuracy. This inaccuracy can be minimized by applying a manual offset correction for the imaging angle. The ICE probe used in this study has a small diameter of 3.3 mm which required rigidly fixing the sensor on the outer sheath of the probe, farther away from the origin of the image. The rigid and outer positioning of sensor lead to some

hardware constraints resulting in our inability to turn and guide the probe into the branches of the vessel. For a clinical system, the EM sensor must be integrated inside the US catheter to achieve accuracy in tracking, freedom in motion and patient safety from an active element. In the future, we plan to collaborate with the ICE probe manufacturers to acquire ICE probes embedded with EM sensors and designing a prototype of the US guidance system presented as a concept study in this paper.

The proposed US-based vascular navigation system can be implemented using many catheter-based US technology, such as radial IVUS probes that are regularly used during cardiac and endovascular interventions. Other than tracking, the accuracy of a clinical vessel reconstruction algorithm will also largely depend on the accuracy of lumen segmentation from in-vivo imaging. The appearance of a vessel in an intravascular or intracardiac US image varies significantly depending on the size and composition of the vessel, as well as the surrounding tissue and organs. The phantom images presented in this study replicate the US imaging of the infrarenal portion of IVC only. Even the echogenicity of the IVC changes as it passes through the abdomen. Thus a clinical system, implementing the proposed idea of US navigation, will require a robust deep learning-based segmentation pipe-line, which is capable of accurately identifying and segmenting all vascular structures as well as vessel branches and tributaries. Existing network architectures, such as U-Net, might be a suitable option for medical image segmentation. Since this is a pilot, proof of concept study for navigation with relatively restricted imaging data, we did not include any learning based approaches for segmentation and relied on conventional image processing techniques.

In future work we aim to improve this vascular reconstruction pipeline by replacing the image-processing based vessel segmentation algorithm with a deep learning-based segmentation technique trained on animal images acquired using the forward-looking, Foresight™ICE probe. The use of machine-learning for vascular segmentation and reconstruction has been previously performed using both surface US scans (Groves et al., 2020; Yang et al., 2013) and intravascular US (Yang et al., 2018). The integration of a machine-learning based segmentation will allow for accurate patient specific reconstructions to be obtained that account for differences in patients pathology. The segmentation algorithm can be trivially replaced within our vascular reconstruction pipeline such that the different vessels required for navigation can be reconstructed using a robust segmentation algorithm capable of delineating various vascular morphologies and side vessel branches, allowing for safe navigation from the insertion site to the central venous system.

Conclusions

Transcatheter interventions provide a low-impact means of delivering therapy using miniaturized equipment and medical imaging technologies. Vascular navigation is a ubiquitous process as it is a prerequisite to reach the target organ or target site in another vessel. The current standard of care employs fluoroscopic techniques or the use of CT vascular mapping, both of which come at a cost of radiation exposure and wearing heavy, shielding aprons. Through this study, we aim to initiate a discussion on the merits of moving towards the use of ultrasound-based instead of radiation-based techniques for transcatheter and endovascular interventions. We present a

proof of concept study to use catheter-based US technology, equipped with tracking sensors, to create a vascular roadmap. Results indicate that the geometric accuracy is comparable to that observed in CT mapping. The concept demonstration (Fig. 4) shows side by side that an US-guided system can provide the same level of information and in three dimensions without the hazards of radiation and lead shielding.

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Figure Captions

Figure 1: Data acquisition setup - Ultrasound probe scans the vessel phantom present within the tracking space.

Figure 2: (a) Image data acquired using a framegrabber as a 2D projection of the conical ultrasound. (b) Lumen segmentation (boundary) achieved using the initial seed (solid). (c) Conical reconstruction of the ultrasound image and the lumen segmentation.

Figure 3: Image a) depicts the skeleton of the vessel comprised of spatially calibrated segmentations, Image b) depicts the ultrasound (US) reconstruction registered to the segmented CT scan of the phantom, and Image c) provides a visualization of the surface-to-surface distance analysis between the US and CT models.

Figure 4: An example use case for navigating a tracked guidewire within the ultrasound reconstructed vessel (b) as compared to the fluoroscopic equivalent (a)

Tables

Table 1: Summary of the metrics use to quantify The spatial overlap and boundary accuracy of the ultrasound reconstructed vessel compared to the vessel segmented from the CT scan of the phantom.

Spatial Overlap	**Value**	**Hausdorff Distance (mm)**	**Value**
DICE Coefficient	0.79	Maximum	5.86
Sensitivity	0.70	Average	1.63
Specificity	0.88	95 %	3.16

Figure 1

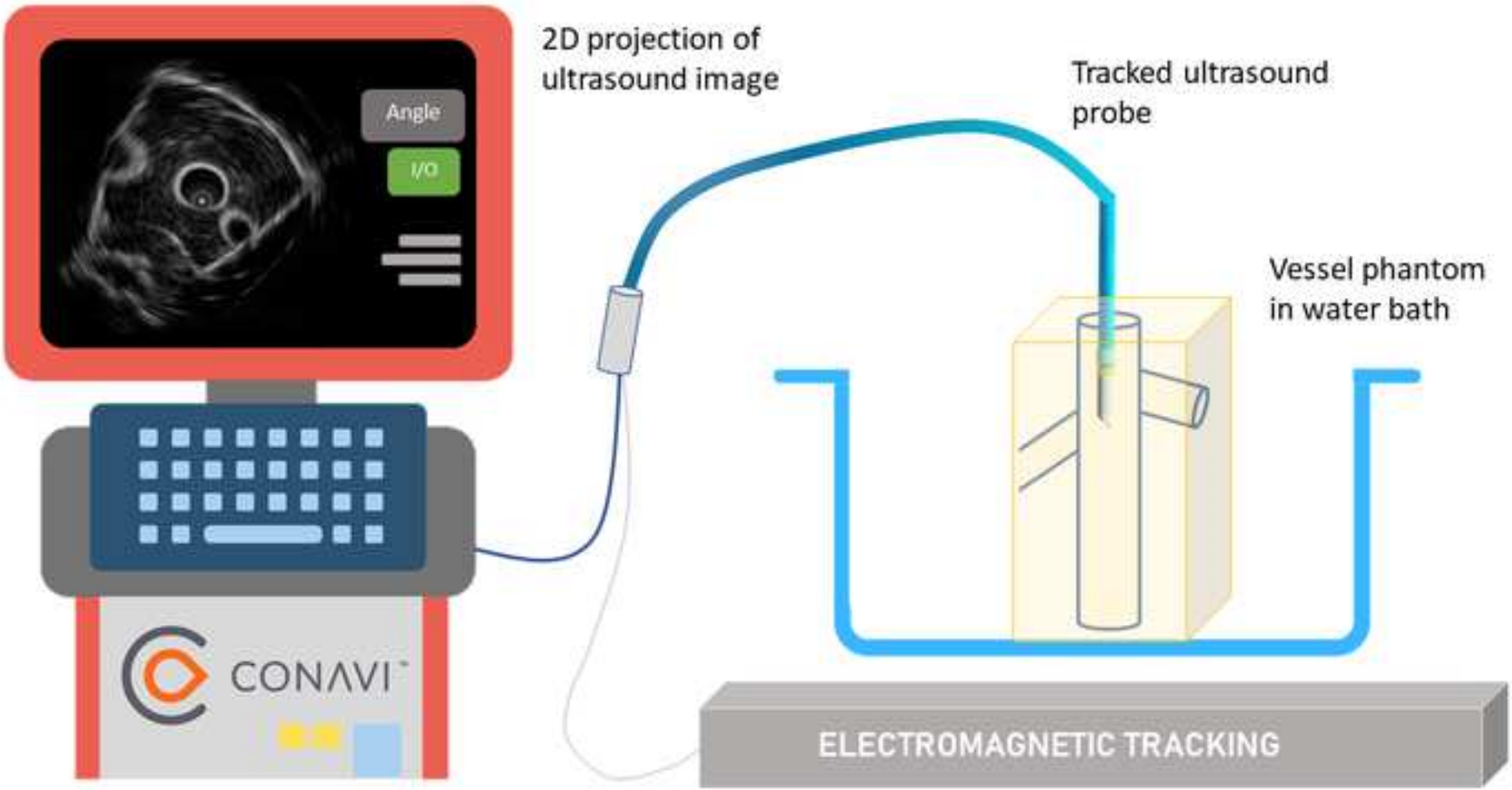


Figure 2

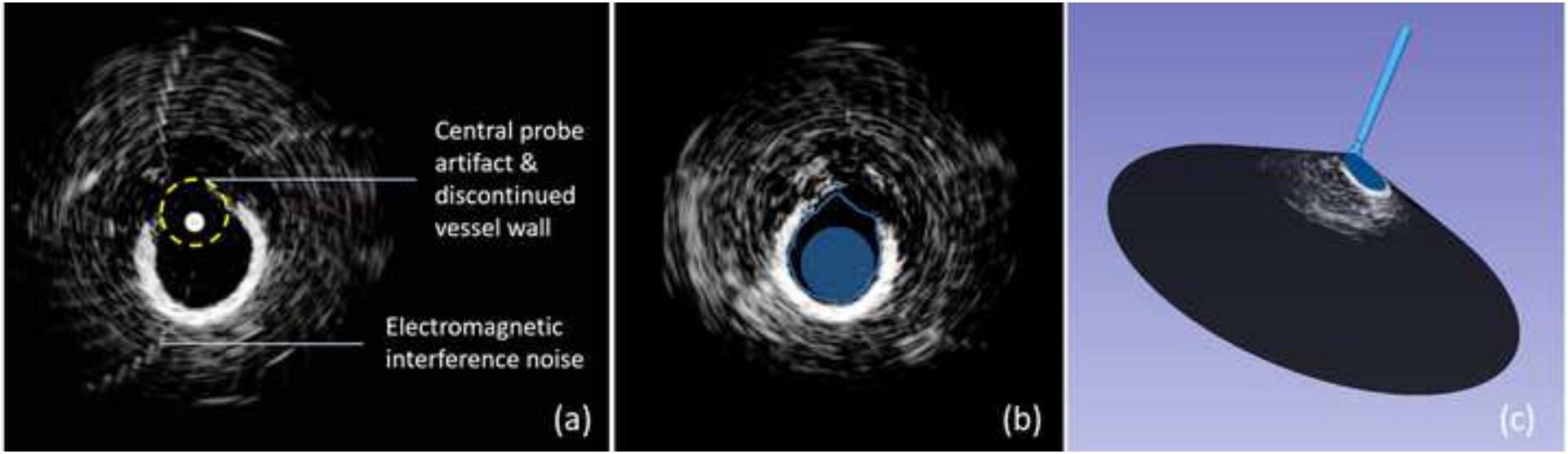


Figure 3

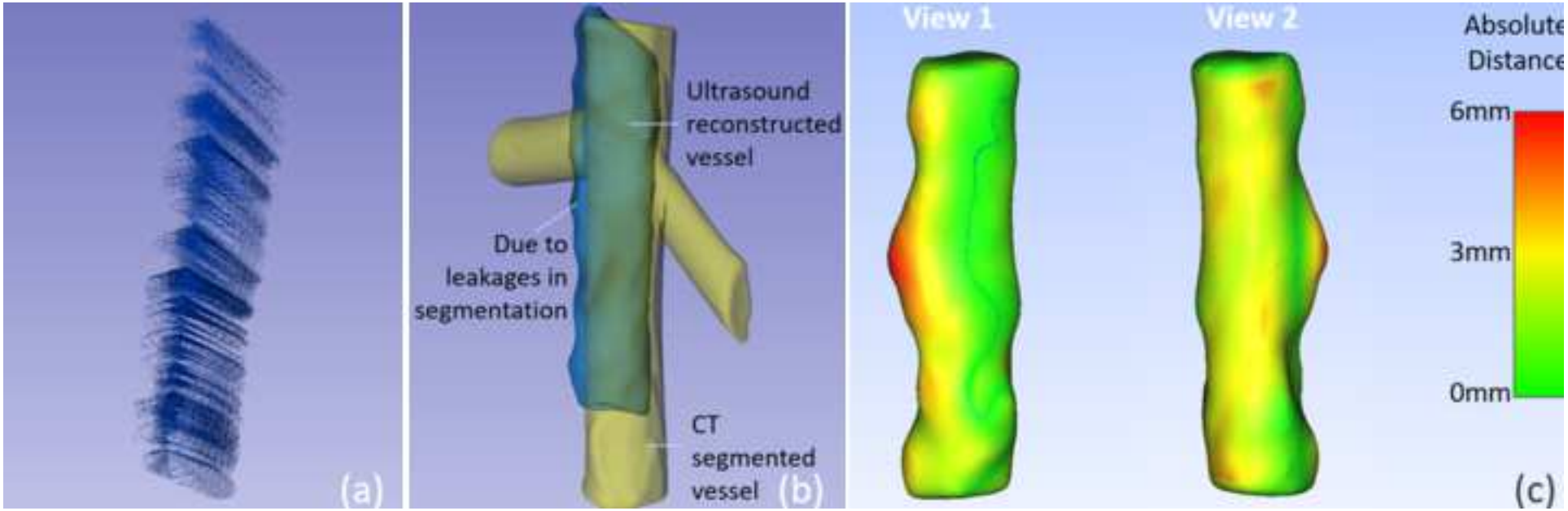
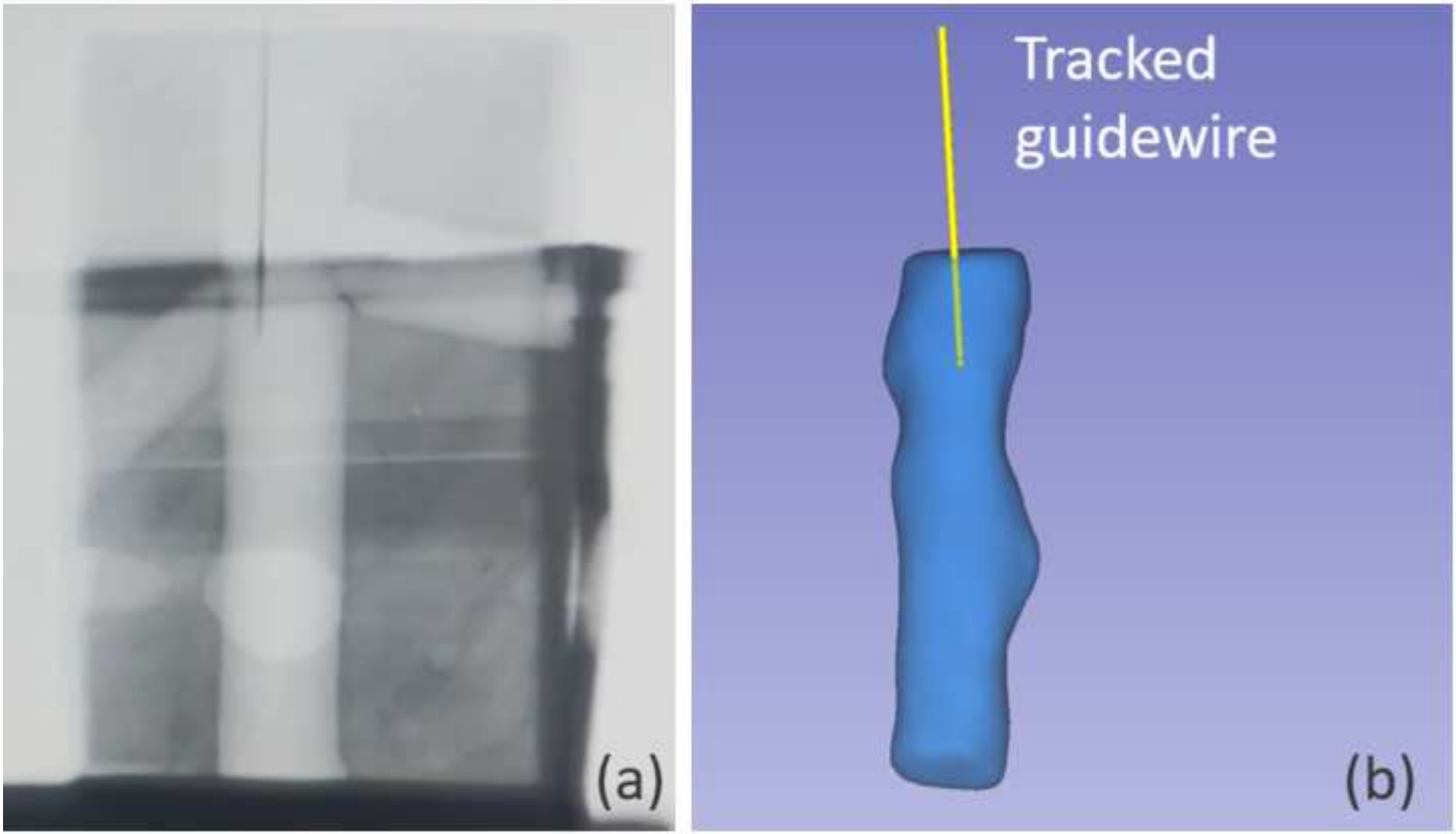


Figure 4



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