An open-source 3D Slicer module for fluoro-free transcatheter vessel navigation

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ABSTRACT

Vascular navigation is an essential component of transcatheter cardiovascular interventions, conventionally performed using either 2D fluoroscopic imaging or CT- derived vascular roadmaps which can lead to many complications for the patients as well as the clinicians. This study presents an open-source and user-friendly 3D Slicer module that performs vessel reconstruction from tracked intracardiac ultrasound (ICE) imaging using deep learning-based methods. We also validate the methods by performing a vessel-phantom study. The results indicate that our Slicer module is able to reconstruct vessels with sufficient accuracy with an average distance error of 0.86 mm. Future work involves improving the speed of the methods as well as testing the module in an in-vivo setting. Clinical adaptation of this platform will allow the clinicians to navigate the vessels in 3D and will potentially enhance their spatial awareness as well as improve procedural safety.

Keywords: transcatheter vessel navigation; tracked intracardiac ultrasound (ICE); fluoro-free

1. INTRODUCTION

Transcatheter interventions are characterized by their minimally invasive nature, enhanced patient safety, and shorter hospital stays,[1] however, they face the challenge of missing a direct line of sight with the tools and the anatomy. Cardiac interventions employ a transfemoral navigation approach where the heart chambers are accessed through a puncture in the femoral artery or the vein and traversing the vessels under fluoroscopic guidance. For endovascular procedures, many vessel branches must be traversed in order to gain access to the target vessel using a CT-derived pre-mapped vascular roadmap or using live X-ray imaging with contrast agents. These current standard-of-care procedures expose the patients as well as the medical staff to harmful radiation causing high-grade skin injury and renal failure in patients and eye cataracts, increased risk of cancer, and thyroid gland disease in the medical team. The lead aprons used to shield the operators are also known to cause back, neck, and spinal issues for interventionalists. As an alternative to these radiation-based methods, Nisar et al.[2] proposed an ultrasound-based workflow where a tracked, radial intracardiac echocardiographic (ICE) probe can traverse and scan the vessels and generate a vascular roadmap in 3D for a tracked guidewire to follow. The same group also developed deep learning-based methods for segmenting vessel lumen from ICE imaging in real-time.[3]

In this work, we aim to combine the abovementioned ICE-based vessel navigation workflow with the deep learning-based segmentation methods in order to create a complete, open-source, and user-friendly 3D Slicer module[4] as a prototype of a platform that can be easily used by a clinician. The development of a customized 3D Slicer module allows for the methods to be seamlessly used during in-vivo experiments as well as further testing for clinical usage and feasibility. In this paper, we present the design of a customized 3D Slicer module which can be used to generate a vascular roadmap for cardiovascular interventions, as well as validating it using a vessel phantom. The accuracy of the ICE-generated vessel is established by comparing it to the CT-derived vascular roadmap.

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2. METHODS

2.1 3D Slicer Module Workflow

The Slicer module implements the methods from[2,3] with two major modifications – A) the vessel segmentation portion of the vessel reconstruction pipeline is replaced with a deep learning-based solution provided by,[3] and B) updated methods are used during the last surface reconstruction step. The complete Slicer module along with some test data can be found at https://github.com/hareem-nisar/Vascular-Navigation. The module framework begins with loading the data and ends with producing a 3D model of the vessel surface. A brief description of each of the steps is given below:

- *Load Data:* The vessel (phantom or patient) is scanned using a magnetically tracked, radial ICE probe, and the imaging and tracking data is loaded to a 3D Slicer using the Data module in the form of a "sequence". The probe calibration matrix is loaded into Slicer as a "transform".
- *Parameter Selection:* Once the data are correctly loaded into Slicer, the user selects them in our customized module. Additionally, a user can select how many frames they would like to reconstruct from the sequence and the approximate vessel diameter (in pixels). The last parameter i.e., imaging angle is specific to the forward-looking angle of the conical Foresight™ ICE imaging probe.
- *Vessel Segmentation:* The vessel reconstruction algorithm works by first segmenting the vessel lumen region from ICE ultrasound imaging, and then placing the segments in their respective 3D space. In our Slicer implementation, vessel segmentation is performed using deep learning-based methods which allow for real-time processing of imaging frames. A pre-trained U-Net model as described by Nisar et al.[3] processes 2D ICE images and produce a corresponding 2D lumen segment. The model is currently trained on animal (swine) inferior vena cava images acquired using a Foresight™ ICE probe, which is characterized by its 2.5D conical surface images.
- *Lumen Reshaping:* Since the segmented regions are extracted from the 2D, flattened version of a conical, 3D ICE image, an additional step is required to convert the segmentations to their true conical shape. Each segmented region undergoes a reshaping function based on the imaging angle ϕ of the Foresight™ ICE probe.
- *3D Reconstruction:* Next, each segment is operated upon by a calibration matrix using the "Transforms" module, as well as a probe-tracking transform that represents the 3D location of the probe when the respective image was acquired.
- *Closed Surface Representation:* To initiate the surface reconstruction process, a closed surface is created for all of the segmentations, and appended to a polydata structure whose final representation containing the full structure of the desired vessel is then imported as a single segment using the "Segmentations" module.
- *Surface Generation:* Finally, the surface is reconstructed by applying three operations or "effects" from the "Segment Editor" module including wrap solidify effect, followed by margin growing by 1 mm and morphological closing using a 3 mm kernel.

2.2 Phantom Validation

The customized module was tested using a phantom experiment. An ultrasound imaging-realistic vessel phantom was placed in the field of a magnetic tracking system (MTS) and scanned using a tracked and calibrated Foresight™ICE probe. The image and tracking data were acquired in the form of a sequence and processed to reconstruct the vessel in 3D. The accuracy of this US-reconstructed vessel is validated by comparing it to the 3D vessel derived from the CT scan of the same phantom.

3. RESULTS

3.1 Slicer Module Design

Our Slicer module, designed to reconstruct a vessel from tracked ICE imaging, has three selection buttons as well as three user-controlled parameters in the interface. The module is user-friendly, allowing the user or the clinicians to run all the reconstruction steps with a click of a button. Figure 1 shows the layout for the slicer module that the user will interact with. Upon running the module, the user only sees the final 3D reconstructed vessel as an output.

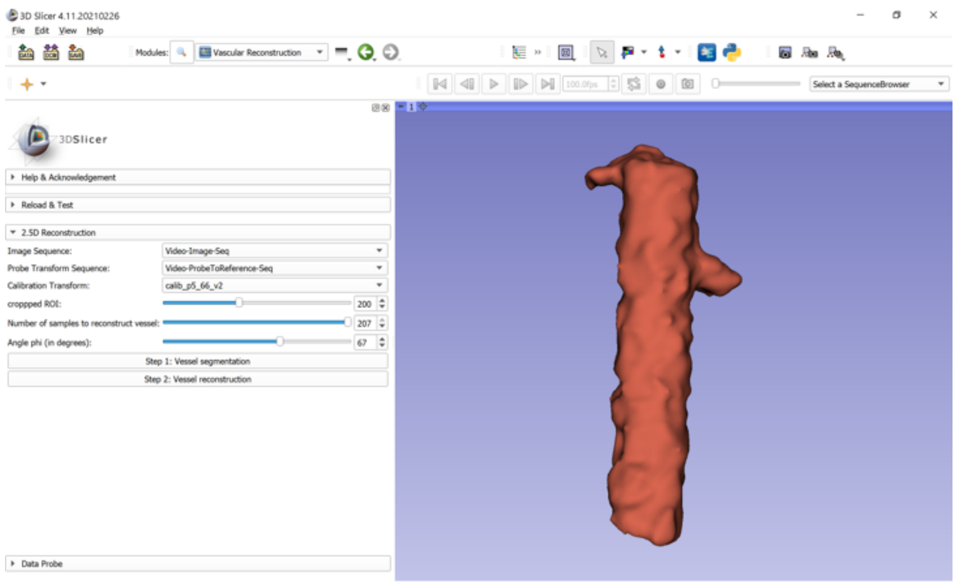

Figure 1. Screenshot of our customized Slicer module showing parameter selection buttons and 3D visualization of the reconstructed vessel.

3.2 Phantom Experiment Results

The accuracy of the ICE-reconstructed vessel was validated against the vessel segmentation derived from a CT scan of the same phantom. The results indicate that the average Hausdorff distance error between the surfaces is 0.86 ± 0.81 mm with a maximum of 5.04 mm. The accuracy of vessel reconstruction in terms of spatial overlap is given in Table 1, where the overall DICE score is 0.86. Only 1.2% of the reconstructed vessel region lied outside the ground truth (false positive). 9.9% of the region was false-negative and was missing from the reconstruction. Overall, the ICE-reconstructed vessel exhibited a lower volume than the ground truth vessel segmentation.

Table 1: Accuracy of the ICE-generated vessel in comparison to the CT-derived vessel

Spatial Overlap	**Value**	**Hausdorff Distance**	**Value (mm)**
Dice coefficient	0.86	Average	0.86
Sensitivity	0.78	95%	2.45
Specificity	0.97	Maximum	5.04

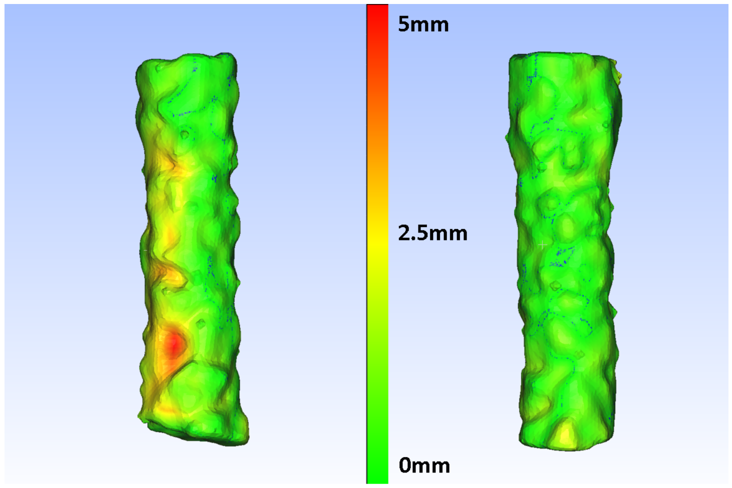

Figure 2. Two different views of the ICE-reconstructed vessel with the colors representing the Hausdorff distance when compared with the CT-derived ground truth.

4. NEW OR BREAKTHROUGH WORK TO BE PRESENTED

This study is the first to present the design of an open-source module that is used to reconstruct the vascular structures from a sequence of tracked ICE images. ICE imaging holds the potential to enhance visualization during transcatheter cardiac and vascular procedures by generating 3D vascular roadmaps. The 3D Slicer module presented in this work implements all the methods - from deep learning based vessel segmentation to vessel surface reconstruction, in the form of a simplified, user-friendly program.

5. CONCLUSION

Vessel reconstruction in 3D has the potential to provide more contextual information to clinicians, and move towards fluoro-free cardiovascular interventions. While methods for real-time vessel segmentation and ultrasound-based vessel reconstruction are part of the literature, further experimentation and in-vivo validation of these methods necessitate a simplified, user-friendly user interface. In this paper, we presented an easy-to-use 3D Slicer module that integrates all the methods required for ICE-based vessel reconstruction and can be intuitively used by a clinician to generate a vascular roadmap for navigation. The results indicate that the customized Slicer module provides sufficient accuracy for vessel reconstruction, as verified by the phantom experiment, and can be used for future in-vivo experiments.

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