Virtually Visualizing Vessels: A Study of the Annotation of Placental Vasculature from MRI in Large-scale Virtual Reality for Surgical Planning

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Abstract—We present a case study evaluating the potential for identifying placental blood vessels using MRI in large-scale virtual reality environments in order to improve the planning of twin-to-twin transfusion syndrome intervention surgery. Twin-to-twin transfusion syndrome is a condition where the blood vessels of twin fetuses are connected on the shared placenta and transfer blood disproportionately between them. This condition is fatal if left untreated as the donor and recipient fetuses will suffer from too little and too much blood, respectively. Treatment of the condition involves endoscopically finding the connections in placental blood vessels and closing them using laser ablation; current clinical practice includes no planning for identifying the locations of these connections before surgery begins. We find that medical professionals are able to identify relevant vessels using our system and that they utilize the larger range of motion allowed by virtual reality, which they do not have while using a traditional endoscope. Our medical professional collaborator and participants believe that by providing surgeons with a way to find these vessel connections before beginning surgery, we can enable them to improve the surgeries and their outcomes.

1 INTRODUCTION

Twin-to-twin transfusion syndrome (TTTS) is a condition that can affect twin fetuses who share a placenta but have separate amniotic sacs; it causes blood to be transferred disproportionately between the two through their connected placental vasculature. The donor can experience stunted growth and development as well as low levels of amniotic fluid, while the recipient can experience heart failure and high levels of amniotic fluid [1]. This condition is fatal if left untreated and its treatment is the most commonly performed endoscopic fetal operation [1]. The condition is diagnosed by looking for the secondary effects on bladder size, amount of amniotic fluid, and overall fetus size using doppler ultrasound, but these methods do not allow the surgeons to actually locate the connections. Instead, once the problem has been identified, surgeons operate using endoscopic laser ablation [2] to close connections between blood vessels and must find all of these connections during surgery rather than during planning.

Our method presents users with a volume rendering of a uterine MRI dataset in a virtual reality (VR) environment and allows them to mark vessels with line segments. We find that medical professionals can consistently identify vessels to the point where this system could be used to plan TTTS procedures and that they quickly adapt to the perspective control afforded to them by VR.

We also find that participants experience difficulty with understanding the depth of their annotation tool in the virtual environment, which causes their resulting annotations to be view-dependant.

2 RELATED WORK

2.1 Motivation

This research was motivated by a strong need to ensure safety in fetal procedures due to the extreme vulnerability of fetuses during development.

In 2001, McCloy et al. [3] describe the impact that virtual reality and robotics will continue to have on surgical planning. They discuss the ability to practice procedures and the effect that can have on the outcome of the surgery. We utilize the potential of VR to approach the shortcomings of TTTS surgical planning in an attempt to improve it.

In 2015, Pratt et al. [4] published a systematic review discussing how the uterine environment makes surgery difficult and how other specialties have used computer-assisted surgical planning to great benefit. They suggest that the development of fetal-specific surgical planning systems is very much needed. We begin to address this problem with our system of viewing the placenta from MRI data in VR to plan for TTTS surgery.

2.2 Placental Visualization

Visualizing the placenta is an important problem when considering planning fetal procedures.

Wang et al. [5] introduced Slic-Seg in 2015 to use machine learning to generate better segmentations of the placenta with minimal interaction by a user. In 2016, Wang et al. [6] improved Slic-Seg by augmenting it with multiple volumes taken from different views. We use linear transfer functions and dynamic lighting in the rendering to address the problem of clearly visualizing the placenta as well as manual segmentation to remove only the fetus, which allows us to leverage the strengths of VR and let participants explore the placenta and its surrounding environment.

2.3 VR Surgical Planning

VR has been used in the past to improve surgical planning.

In 2000, Kockro et al. [7] developed VIVIAN, a system that uses patient-specific data from multiple different
scanning technologies and displays the preregistered data as a stereoscopic 3D object. They allowed manipulation, measurement, and simulation in neurosurgical planning. We use augmented volume rendering of a single MRI scan, so no data registration is required, and we explore the strengths of the visualization in helping participants find the vessels.

Also in 2000, Kühnapfel et al. [8] explored using virtual reality to practice endoscopic procedures. They implemented a system that supported actions on deformable objects, like grasping and applying clips, as well as force feedback. We attempt to improve planning by mapping the placental vessels to prepare for surgery instead of practicing it.

In 2001, Xia et al. [9] developed a VR system for orthognathic surgical planning which allowed for simulation of surgery based on CT scans and included soft-tissue prediction for the outcomes of different facial reconstruction procedures. We use annotation instead of modification of the data as well as focus on the placental vasculature.

In 2001, Luks et al. [10] showed the benefits of using volume renderings of uterine MRI scans to plan TTTS procedures on a desktop computer. This system allowed for the understanding of the spatial relationship between the placenta, the umbilical cords, and the fetuses but could not visualize the communicating vessels on the placental surface using MRA. Our approach does allow for viewing vessels which are small enough to be connections in cases of TTTS.

In 2004, Grantcharov et al. [11] found that surgeons trained on virtual reality simulations performed significantly better than those who did not for a laparoscopic cholecystectomy. After our experiment, our collaborator also believes that our system could help train surgeons for TTTS surgery, that the free-hand technique of identifying the surface of the vessels may be a good training ground for laser ablation, as the YURT navigation can help train the surgeon in correctly placing the laser focus on the vessel wall without tactile or haptic clues.

2.4 VR Interaction

As part of a VR system, we need to consider the effects of different aspects of VR.

Keefe et al. [12], in 2007, described the difficulties of 3D tracing tasks in VR. They found that freehand 3D tracing is difficult even when augmented with simulated friction haptic feedback, so they developed a controlled tracing method to simplify drawing curves in 3D space. We chose to instead require that participants draw line segments instead of curves; this reduced some of the difficulty of freehand tracing and required much less training than the controlled tracing method.

In 2008, Forsberg et al. [13] studied desktop, fishtank, and CAVE displays for use with the exploration of confocal microscopy volume rendering datasets. They found that the subjects performed better and preferred the CAVE system, so we chose to hold our study in the YURT, our advanced CAVE system.

Similarly, in 2012, Laha et al. [14] studied components of immersion in VR volume data visual analysis tasks. They found that head-tracking, high field of regard, and stereoscopic rendering have a high positive effect on the performance of users in visualization tasks. In 2014, Laha et al. [15] found that stereoscopic rendering has a higher positive effect in search and spatial judgement tasks for isosurface renderings, while high field of regard and head tracking have a higher positive effect with the same tasks for 3D texture volume renderings; high field of regard and head tracking improve spatial judgement tasks for both kinds of visualizations. We leverage these benefits in our experiment with the YURT, and the particular visualization we use is a 3D texture rendering but has properties of isosurface visualizations, so our search task is benefited by these components of immersion.

3 METHODS

3.1 Dataset

Fig. 1. This is a rendering of the MRI volume seen by participants in the YURT.

The dataset given to participants was a uterine MRI scan of a singleton fetus, shown in Fig. 1, with a voxel size of $0.7 \times 0.7 \times 1.2$ mm. The image slices had a resolution of $512 \times 512$ pixels, and we used 45 of them to show the area covered by the placenta. The fetus was manually removed from the data to reduce occlusion by setting its scan intensity values to that of the surrounding amniotic fluid; unfortunately this also obscured some areas where the fetus was lying atop parts of the placenta.

3.2 Tools

We carried out our experiment within the YURT (YURT Ultimate Reality Theater) Brown University’s advanced CAVE display [16], shown in Fig. 2. It is equipped with 69 high definition stereo projectors which use rear projection to illuminate a cylindrical wall, cylindrical doors, a conical ceiling, and a 135 ft² elliptical floor. Within the YURT, users wear Volfoni 3D glasses and use an Aimon PS wireless wand.
controller, both of which are shown in Fig. 3. They are both tracked by an array of OptiTrack infrared cameras on the ceiling of the YURT, which can be seen in Fig. 2. For a user standing in the center of the YURT, it has a resolution of 1 pixel per arcminute and a visual surround of $3.8\pi$ steradians. It also has optical tracking for a user’s head and wand devices.

The application we used for the study is 3DVisualizer, a volume renderer built upon the Vrui (Virtual Reality User Interface) toolkit [17]. Both the application and the toolkit were created by Oliver Kreylos at the UC Davis W.M. Keck Center for Active Visualization in the Earth Sciences (KeckCAVES). We augmented 3DVisualizer to support illuminating the volume rendering with a light source at the user’s head position and added regularly-spaced a 3D grid to augment users’ understanding of the space.

While viewing the dataset, participants were able to move around in 3D space to see it from different perspectives; they were also able to use the wand to move the dataset itself with 6 degrees of freedom. The application was additionally configured to allow users to draw line segments, rendered as red cylinders, in 3D space in order to annotate the dataset. A menu was presented to users allowing them to indefinitely remove the most recently drawn remaining segment as well as remove all remaining segments at once. A user drawing these segments can be seen in Fig. 4.

3.3 Participants

We recruited eight medical professionals to participate in the study. Each one came from either Rhode Island Hospital or Women & Infants Hospital of Rhode Island, and they all have experience working with placental anatomy.

3.4 Procedure

For every study session, we brought a participant to our facility. We began by introducing him/her to the equipment and the dataset as well as explaining the interaction methods. We also informed the participants of the camera placed in the YURT to record video of the session and the microphone on provided headphones to record audio as well as the fact that we were saving their tracings and interaction logs of their time using the application.
We asked the participant to practice tracing the edge of the dataset in order to verify his/her ability to trace in 3D space. We did not stop training until we were sure that the participant understood tracing in 3D space and how spatial depth makes it differ from tracing something on paper.

![Image](58x504 to 290x678)

**Fig. 5.** This is an example of a full vessel tracing on the MRI volume dataset created by our expert collaborator in the YURT and used to produce our ground truth.

We then cleared all tracings and moved onto the trials. Each participant did three trials where the goal was to trace all the blood vessels on the surface of the placenta. This included searching the placenta to find vessels and decide what to qualify as a vessel as well as marking those things decided to be vessels properly with line segments, rendered as red cylinders. An example tracing, done by our expert fetal surgeon collaborator, is shown in Fig. 5.

Because annotations were made with segments, we told the participant that we expected him/her to use a larger number of shorter segments in areas of high curvature of the vessels in order to accurately represent the shape instead of using a smaller number of longer ones that would create a more rough approximation. The participant was also asked to speak his/her thoughts about the data and task aloud so we could record and study them and gain insight into the utility of the visualization and interaction.

After finishing the three trials, the subject was given a free-form interview and asked about the visualization, the experience, and any potential application of the technology.

Each participant’s session lasted approximately 30 to 45 minutes in total.

### 4 Results

As part of our analysis, we created a ground truth set of tracings, shown in Fig. 6, for comparison with those of the participants. These ground truth tracings were created by our fetal surgeon collaborator in the same three trial structure but were based on his extended experience with the data and the equipment.

#### 4.1 Projections

Very few tracings actually fell on the surface of the placenta because of users’ inexperience with 3D VR interactions and the difficulty of simultaneously searching for vessels and remembering to keep the cursor on the placental surface while tracing them with no haptic feedback. In addition to seeing that the segments were most often floating above the surface of the dataset, we were also told by the participants that they knew they were not consistently tracing on the surface because they could not sufficiently concentrate on both the search task and maintaining contact with the placenta while tracing.

To remedy this for the ground truth, we manually projected the expert’s tracings onto the surface of the placenta. For the participant tracings, we recorded their head positions at the time that each segment endpoint was created and used the lines passing through each pair of head and tracing positions as a measure of intentionality to correct for the difficulties seen with 3D tracing.

#### 4.2 Ground Truth Comparison

![Image](322x152 to 554x281)

**Fig. 6.** The ground truth tracing created by our expert collaborator projected into the YZ plane.

![Image](560x758)

**Fig. 7.** This is a histogram of tracing segments drawn by participants and organized by their distances from the ground truth tracings. The bins are of size 1 mm.

Over 75% (878 out of 1157) of tracing segments fell entirely within a 2 mm margin of error of the ground truth tracing when projected from the head position, as can be seen in Fig. 7, and all of the ground truth tracing was identified. From our results, it is clear that people...
can identify placental blood vessels to an estimated 1 mm diameter from an MRI visualization in VR because the vessels identified by the participants reached this small size. Because of the reproducibility of these tracings between participants, it is also clear that it is possible to identify twin-twin communicating vessels of the artery-artery and vein-vein variety, as they do not change in diameter. According to our expert collaborator, this may allow for the location of hidden vessels, or those which are difficult to detect, while planning the surgery. Fig. 8 shows all participant tracings and identifies which segments fell within 2 mm of the ground truth and which did not.

Fig. 8. These are the segments from all participant trials overlaid on the ground truth. The ground truth is shown in black; segments with projections within 2 mm of the ground truth are shown in green; and segments outside that area are shown in red.

4.3 Head Movement
We also found a very high level of head movement with our tracings. User head positions varied by 45.24, 173.99, and 106.49 mm along the X, Y, and Z axes, respectively, relative to the dataset. That is 307.78, 1183.74, and 724.51 mm, respectively, in real-world scaled space, as the model is scaled up to approximately 6.80 times its actual size. This differs from the endoscopic view used during surgery because the range of motion of the endoscope is more limited.

Fig. 9 shows each participant’s tracings along with the lines that indicate where a participant’s head was when he/she drew each segment. For example, it is clear in Fig. 9 that Participant 3 used about 3 or 4 different head positions to trace the vessels based on the more focused clusters of head-wand lines; however, Participants 5 and 8 showed many more, less defined clusters and, therefore, moved around many times during tracing.

Fig. 9. This is a comparison of head movement across all eight participants; each plot is labeled by its participant number, and all three trials from that participant are overlaid. Red lines are those drawn by participants, while gray lines connect each user’s head and wand positions for each segment he/she drew.

5 DISCUSSION
5.1 Disagreement
There was some variability between participants with respect to the ground truth and to each other, which can be seen in Fig. 10. For example, Participant 3 missed the central vertical vessel defined by the ground truth but identified two additional undefined vessels, while Participant 6 found most ground truth vessels but also identified additional undefined vessels, including part of those identified by Participant 3. All participants missed some part of the ground truth tracing and traced something that was not found to be associated with any piece of the ground truth. These may come from many different sources of error.

There is the difficulty inherent in the annotation method. As described by Keefe et al. [12], drawing on air is difficult; this is true of precisely placing endpoints of 3D line segments as well. It becomes even more difficult as participants are trying to do that as well as identify vessels, which itself requires a great amount of concentration; multiple participants remarked that it was challenging to focus on both identifying vessels and tracing them accurately. This is further exacerbated by the length of time spent doing both of these things.

There were also varying levels of confidence between participants. During the sessions, some remarked that anything they thought might be a vessel would be annotated, while others preferred to only target those of which they were certain. Some participants even traced features disconnected from the main vasculature because they thought the vessels may have submerged beneath the surface and emerged again further from the insertion point.
6 Conclusion

We presented a case study evaluating our virtual reality system for finding placental blood vessels using a visualization of MRI data. We found that medical professionals are able to identify the vasculature responsible for TTS using our system and can, therefore, improve surgical outcomes by reducing time spent in utero. We also found that participants moved their heads around very often to get many different perspectives, which gives us insight into the ways people prefer to study the placental vasculature with unrestricted movement.

References


