# Towards Placental Surface Vasculature Exploration in Virtual Reality

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We present a case study evaluating the potential for interactively identifying placental surface blood vessels using magnetic resonance imaging (MRI) scans in virtual reality (VR) environments. We visualized the MRI data using direct volume rendering in a high-fidelity CAVE-like VR system, allowing medical professionals to identify relevant placental vessels directly from volume visualizations in the VR system, without prior vessel segmentation. Participants were able to trace most of the observable vascular structure, and consistently identified blood vessels down to diameters of 1 mm, an important requirement in diagnosing vascular diseases. Qualitative feedback from our participants suggests that our VR visualization is easy to understand and allows intuitive data exploration, but complex user interactions remained a challenge. Using these observations, we discuss implications and requirements for spatial tracing user interaction methods in VR environments. We believe that VR MRI visualizations are the next step towards effective surgery planning for prenatal diseases.

We present results from a study evaluating the potential of virtual reality (VR) visualizations to identify surface blood vessels in a magnetic resonance imaging (MRI) scan of a human placenta. This work is motivated by the need for better methods for analyzing placental vessel structures and planning fetal surgical interventions. Vascular anatomy is typically explored in the diagnosis and treatment of several pregnancy disorders, including the main research area of our collaborators: twin-to-twin transfusion syndrome (TTTS). TTTS is a rare and potentially lethal condition affecting twin fetuses who share a placenta but have separate amniotic sacs; it causes disproportional blood transfer between the two through communicating placental vessels. Both fetuses are at very high risk of dying in utero[1]. In clinical practice, TTTS is diagnosed by ultrasound (US)[2]. While surgical planning from 3D medical imaging is possible, it is not yet possible to map out the harmful placental interconnections in advance[3]. Vascular anatomy is usually visualized by injecting radio-opaque contrast agents directly into a patient's blood vessels (angiography). This approach is not appropriate in the fetus, as puncturing its blood vessels would be too invasive, and contrast agents would be potentially toxic. Thus, surgeons typically only identify problematic vessels connections at the time of surgery, preventing meaningful planning of the intervention.

Our experimental evaluation shows that expert users can effectively identify relevant blood vessels in magnetic resonance imaging (MRI) scan visualizations using a VR environment. Study participants were shown a direct volume rendering (DVR) of a uterine MRI scan and were asked to mark vessels with cylinder segments in their 3D locations. We found that medical professionals quickly adapted to the intuitive perspective control in VR systems and identified placental vasculature accurately and consistently without the use of contrast-agents or prior vessel segmentation in the dataset.

The following sections describe the motivation for our work and its context in prior studies. We then present our experimental setup, procedures and collected metrics followed by a discussion of our findings. Finally, we report our conclusions on the effective use of VR for placental MRI scan exploration.

## SIDEBAR: VIRTUAL REALITY IN MEDICINE

Virtual reality offers an intuitive way to visualize and interact with spatial 3D data. and has been successfully employed in the medical field since the early 1990s. Applications since then range from educational and therapeutic systems to medical image analysis tools and training simulations[1]. In 2001[2] McCloy et al. summarized the impact of virtual reality and robotics on surgical planning and pointed to their use in analyzing medical scans and the effect of practice on surgical outcomes. Pratt et al.'s systematic 2015 review discussed the difficulties of surgery in the uterine environment and described the success in other specialties of computer-assisted surgical planning, suggesting that fetal-specific surgical planning systems are very much needed[3]. Our work addresses this problem by evaluating VR exploration of placental MRI scans as a potential new tool for diagnostics and treatment planning.

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2. R. McCloy and R. Stone, "Virtual reality in surgery," Br. Med. J., vol. 323, no. 7318, p. 912, 2001.
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## SIDEBAR: PLACENTAL VISUALIZATION

The size and structural features of the placenta can be important indicators for complications during a pregnancy. Analyzing in-vivo scans of the placenta from medical imaging data (usually ultrasound) is common practice in prenatal care[1]. The now wide availability of 3D scanning modalities offers new opportunities for a more accurate diagnosis. Luks et al. showed the benefits of volume renderings of uterine MRI scans in planning TTTS procedures on a desktop computer[2]. Their system helped users understand the spatial relationships between the placenta, umbilical cords, and fetuses. However, visualizing small communicating vessels on the placental surface was not possible. Unlike previous work, our approach, which leverages higher-resolution data and 3D VR navigation, lets users inspect vessels that are small enough to be potentially relevant connections in TTTS cases.

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Wang et al. have introduced a semi-automatic system to analyze the placenta in MRI scans. Their Slic-Seq system uses machine learning to generate segmentations of the placenta with minimal user interaction[3]. In follow-up work they augmented Slic-Seg to work on multiple scans taken from different views[4]. A recent approach by Alansary et al. presents a fully automatic segmentation framework for the placenta from motion-corrupted fetal MRIs[5]. Their proposed framework adopts convolutional neural networks (CNNs) as a strong classifier for image segmentation followed by a conditional random field (CRF) for refinement.

In contrast to these related systems, we remove only occluding anatomy (i.e. fetus and parts of the umbilical cord) from the dataset by manual segmentation, to retain the context of the uterus walls in our experimental visualization. The existence of these placenta-segmentation methods suggests that this process can be automated in future experiments.


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3. G. Wang *et al.*, “Slic-Seg: slice-by-slice segmentation propagation of the placenta in fetal MRI using one-plane scribbles and online learning,” in *Medical Image Computing and Computer-Assisted Intervention--MICCAI 2015*, Springer, 2015, pp. 29–37.
4. G. Wang *et al.*, “Slic-Seg: A minimally interactive segmentation of the placenta from sparse and motion-corrupted fetal MRI in multiple views,” *Med. Image Anal.*, 2016.
5. A. Alansary *et al.*, “Fast fully automatic segmentation of the human placenta from motion corrupted MRI,” in *MICCAI 2016: Medical Image Computing and Computer-Assisted Intervention*, S. Ourselin, L. Joskowicz, M. R. Sabuncu, G. Unal, and W. Wells, Eds. Springer International Publishing, 2016, pp. 589–597.


## SIDEBAR: VR INTERACTION METHODS

While VR interaction techniques are generally intuitive, users often require some training to effectively use the full range of capabilities offered by VR environments. Selecting the right interaction methods for a given task is critical in creating a successful application. Several studies have investigated the advantages and disadvantages of VR systems in relation to traditional desktop setups. Pausch et al., comparing a VR interface and a stationary monitor for search tasks[1], found that VR users were no more accurate at finding all targets in the space than stationary monitor users; however, they were significantly faster at determining whether a target existed in the space because they spent much less time reexamining previously searched areas of that space. In the context of medical applications, arriving at a quick diagnosis is an important efficiency consideration and was one of the reasons for our VR experiment.

In 2003, Olwal et al. discussed the difficulties in pointing to VR objects when they are so close together as to cause pointing ambiguity or visual occlusion and introduced a flexible pointer system that improved pointing results in their experiments[2]. Investigating a similar problem, Keefe et al. described the difficulties of 3D tracing tasks in VR[3]. Finding that freehand 3D tracing is difficult even when augmented with simulated friction haptic feedback, they developed a controlled tracing method to simplify drawing curves in 3D space. To avoid these problems, our annotation tool was based on separate line segments instead of continuous curves resulting in reduced difficulty and training time.

Laha et al. 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 positive effect on user performance in visualization tasks[4]. In a follow-up study, they found that stereoscopic rendering has a larger positive effect in search and spatial judgment tasks for isosurface renderings, while high field of regard and headtracking have a larger positive effect in these task categories for 3D texture volume renderings and also improve spatial judgment performance in both

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kinds of visualizations[5]. We leverage these benefits in our experiment with the YURT which offers high fields of view and regard. Our data visualization method mimics the visual properties of isosurface renderings, to gain the benefits reported by Laha et al.


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2. A. O. S. Feiner, "The flexible pointer: An interaction technique for selection in augmented and virtual reality," in *Proc. UIST'03*, 2003, pp. 81–82.
3. D. F. Keefe, R. C. Zeleznik, and D. H. Laidlaw, "Drawing on air: Input techniques for controlled 3D line illustration," *Vis. Comput. Graph. IEEE Trans.*, vol. 13, no. 5, pp. 1067–1081, 2007.
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# METHODS

## Dataset

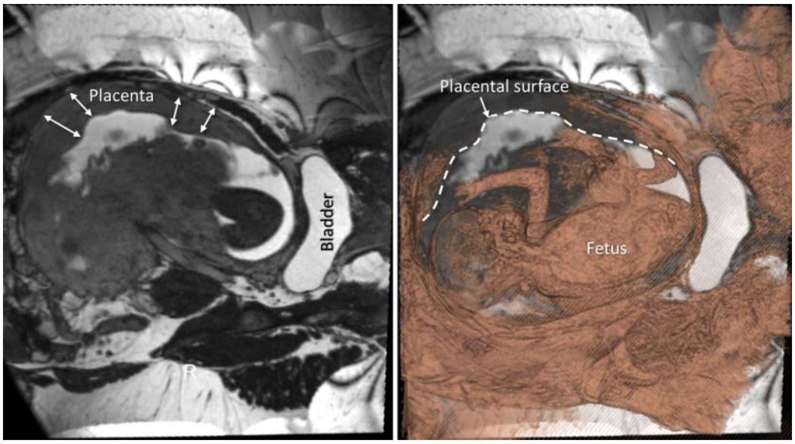


Figure 1. 2D renderings of the MRI scan used in our experiment highlighting placenta and bladder on the left as well as placental surface and fetus on the right. The image on the right contains a partial volume rendering overlay indicating the position of the fetus.

The dataset used in our experiment was a uterine steady-state free precession T2-weighted MRI scan of a singleton fetus, shown in Figure 1, with voxel size 0.7 × 0.7 × 1.2 mm. The image slices had resolution 512 × 512 pixels (resampled from a 256 × 256-pixel acquisition matrix), and we used 45 slices showing the volume containing the placenta. The placenta was aligned with the X-Y plane of the volume with minimal curvature, result figures/plots in this article are therefore projected to this plane.

We used an anonymized MRI scan of a single pregnancy at 25 weeks gestation as a stand-in for proof of principle. The imaging data of the fetus was manually removed from the MRI scan to reduce occlusion of the placenta surface. Unfortunately, this also included areas where the fetus was in direct contact with the placenta, creating stair-shaped rendering artifacts. This manual removal step might be avoided in the future, by using automated methods as discussed in the "Placental Visualization" sidebar. A rendering of the original dataset, including the fetus, is shown in Figure 2, while the rendering shown to participants, without the fetus, is displayed in Figure 5. To ensure that all vessel details were visible, the data were displayed at 6.8 times their original

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size, a scale suggested by our medical collaborators during pilot runs of our experiment. Relevant vessels were only visible on the user-facing side of the dataset, reducing the need to examine the dataset from all sides.

Figure 2. Photograph of the volume-rendered MRI scan including the fetus displayed inside the YURT. The VR visualization was displayed as a 2.4 m-tall virtual object to fully utilize the YURT's available space.

## VR Environment

Figure 3. The Brown University YURT with a user inside. The OptiTrack cameras line the ring and the straight edges of the ceiling.

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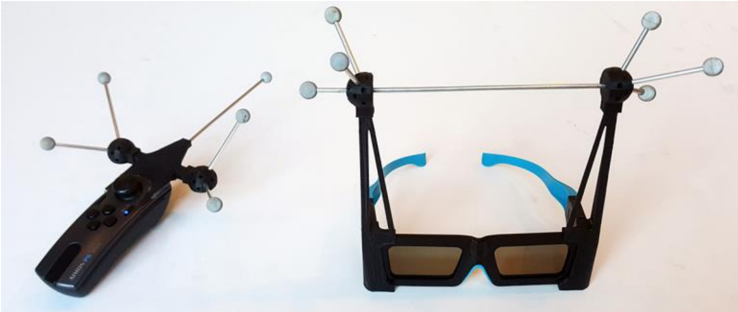

Figure 4. The wand and glasses used in the YURT. Attached to each tool is a constellation of reflective balls used by the optical tracking system to compute its location. The glasses use active shutters with 120Hz frequency to let users see stereo 3D.

We carried out our experiment within the YURT (YURT Ultimate Reality Theater), Brown University's advanced CAVE display[4] (Figure 3). It is equipped with 69 high-definition stereo projectors that use rear projection to illuminate a cylindrical wall, cylindrical doors, a conical ceiling, and a 12.5 $m^2$ floor. For a user in the center of the YURT, the array or projectors provide effective resolution of 1 pixel per arcminute (approximately that of the human eye) and a visual surround of 3.8π radians (about 95% of complete surround). Within the YURT, users wear Volfoni 3D glasses and use an Aimon PS wireless wand controller (Figure 4), both tracked by an array of 8 OptiTrack Prime 13W infrared cameras on the YURT's ceiling (Figure 3).

The visualization software used for the study was based on 3DVisualizer, a volume renderer built using the Vrui (Virtual Reality User Interface) toolkit, created by Oliver Kreylos at the UC Davis W.M. Keck Center for Active Visualization in the Earth Sciences[5]. We augmented 3DVisualizer to support illuminating the volume rendering with a light source at the user's head position and added a regularly spaced 3D grid to augment understanding of the space. Figure 5 shows a view of the dataset from within the YURT; for comparison, Figure 2 shows a typical clinical 2D rendering of the same scan. During the experiment we ensured a frame-rate of at least 50 stereo frames per second.

## Interaction Methods

The YURT offers basic interaction methods expected in a modern room-scale VR environment, allowing participants to move freely around the dataset to investigate it from different perspectives. The wand tools can be used to move the dataset itself with six degrees of freedom.

Annotations are created by placing separate line segments with the wand tool. A line segment is started at the tip of the conical wand marker with the first button press and then stretches to follow the wand tip until its placement is finalized with a second button press. Wand marker and line segments disappear when they enter solid volume data to provide users with an accurate sense of placement depth. Additionally, we gave participants two functions: an undo function to remove the most recently drawn segments, and a reset function to remove all annotations and return the visualization to its original state. In Figure 5 a user draws these line segments.

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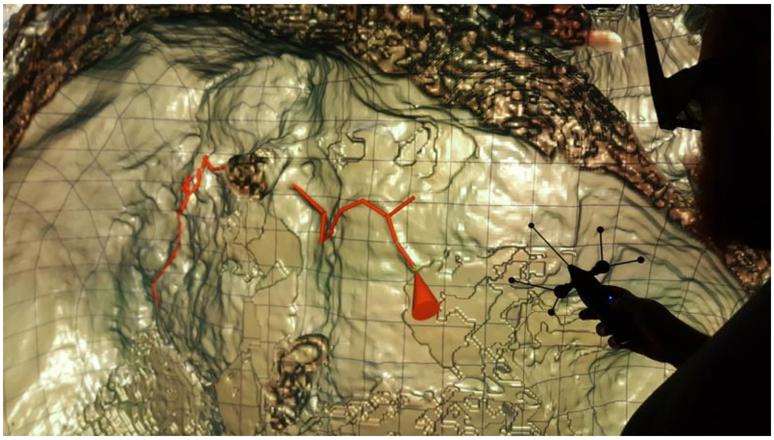

Figure 5. Close-up of a user tracing vessels in our VR setup. The red cone indicates the tip of the wand from user perspective. Annotating line segments are drawn between 2 wand positions confirmed by button presses.

## Participants

We recruited eight medical professionals from Rhode Island Hospital and Women & Infants Hospital of Rhode Island to volunteer as participants of in the study. They all had experience working with placental anatomy.

## Procedure

The experiment was performed at our VR facilities at Brown University. We began by introducing participants to the equipment and the dataset. All available user interaction methods were demonstrated, and participants were given a short time to get used to controlling the environment. We also informed the participants of the camera in the YURT that recorded videos of each session and the microphone on headphones that recorded audio. Additionally, we explained that we were collecting tracings and interaction logs within the application during the experiment.

We asked our participants to practice tracing the edge of the dataset to get used to basic VR interactions. During this initial training stage, we specifically introduced participants to the concept of tracing in 3D space and instructed them to make use of spatial depth in their tracing process; we verified their understanding of the concept visually by inspecting test tracings left by the participants on a predefined target ridge feature. We asked participants to be as accurate as possible and imposed no time limit to allow free exploration of the visualization.

We then cleared all tracings and moved on to the trials. Each participant completed three trials on the same dataset, whose goal was to trace all the blood vessels on the placental surface. This task included searching the placenta for surface structures, decide what should qualify as a vessel, and marking the identified vessels with line segments, rendered as red cylinders. An example tracing is shown in Figure 5.

Because annotations were made with line segments, we instructed participants to use a larger number of shorter segments in areas of high vessel curvature to represent the shape accurately. Participants were also asked to express their thoughts about the data and task during running trials, so that we could record and study them to learn about 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 of exploring medical data in VR, and potential applications of the technology. Each participant's session totaled approximately 30 to 45 minutes. The experimental protocol was approved by our university's IRB.

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## Reference Dataset

To evaluate and analyze the obtained data, we created an expert set of tracings (Figure 6). This dataset was initially created by our fetal surgeon collaborator in the VR environment used for the experiment and benefited from his extensive experience with the data and equipment. However, this reference tracing still included minor offsets from the placental surface. We generated a more accurate reference dataset by projecting the tracing data onto the surface and manually re-traced it with connected line segments at higher resolution using the 3DSlicer open-source medical visualization framework[6].

## Metrics

To compare participant tracing data to the reference dataset it was necessary to re-project line segments onto the placenta. While some tracing segments were located exactly on the placental surface, most were drawn hovering over that surface. We recorded an average offset distance of 2.4 cm across all participants, with outliers of up to 9 cm. This can be attributed to the users' inexperience with 3D VR interactions and the difficulty of simultaneously searching for vessels and keeping the cursor on the placental surface while tracing them without haptic feedback. To overcome this problem in participant tracings, we recorded their head positions at the moment they created each segment endpoint and used the lines passing through each pair of head and tracing positions to identify the intended line segments on the placental surface. This method let us use the distance between the line of sight for each tracing and the closest expert reference point to evaluate how much each participant results agreed with the expert about blood vessel locations.

To compare the obtained participant tracings to the expert dataset we defined all reference segments within 2 mm (patient scale; ~13 mm within the virtual environment) of projected participant tracings as correctly identified. The error distance was chosen together with our collaborator based on the size of vessel features and the expected accuracy in our experimental VR environment. Within our study participant precision was therefore the length of line segments within error range of the reference tracing over total tracing length and sensitivity was the length of correctly identified reference line segments over total reference length.

# RESULTS

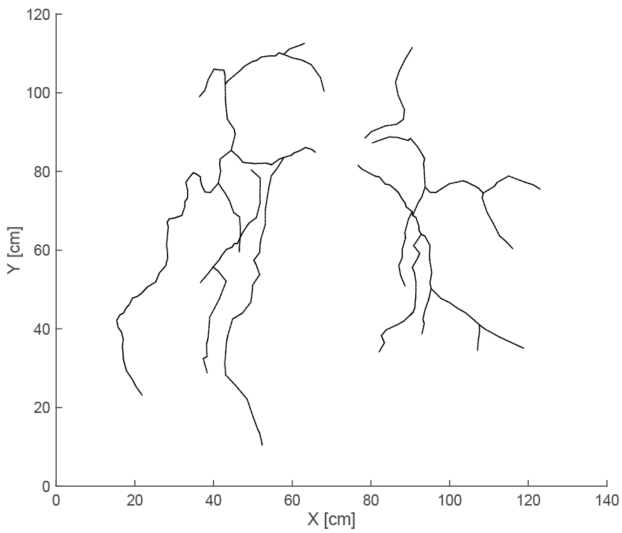


Figure 6. Reference tracing created by our expert collaborator projected onto the XY plane.}

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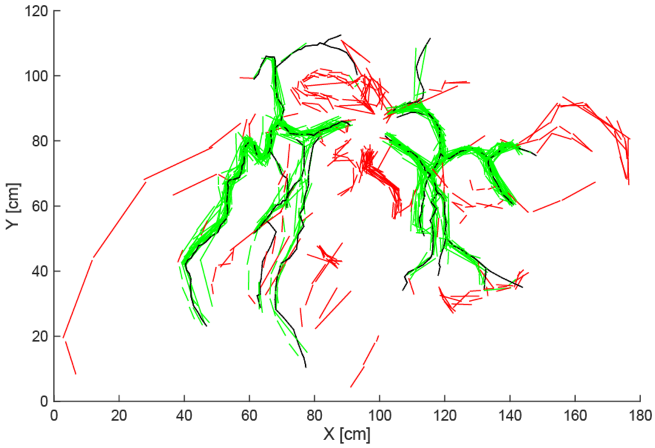


Figure 7. The segments of all participant trials overlaid on the expert reference in the XY plane. The expert reference is shown in black; segments with projections within 2 mm of the expert reference are shown in green; and segments outside that error margin are shown in red. Participant tracings are shown without projection to visualize the offset of tracings from the reference set.}

We found that participants were able to identify blood vessels of 1 mm diameter in our MRI VR visualization, a size relevant to the diagnosis and treatment of vascular diseases like TTTS. Figure 7 shows the results of all participant tracings, color-coding the segments which fell within 2 mm of the expert reference green, and those that did not red. Most participants achieved a tracing precision greater than 75% when evaluated against the expert reference tracing, with a lower bound of 59.8%.

Detailed analysis shows notable variability among participants with respect to the expert reference and to one another (Figure 8). Table 1 lists the individual quantitative results. While individual total coverage varied greatly, we see that most tracing results fell within the margin of error for each participant. We found that most participants were conservative in annotating vessels and often did not trace them as far the expert user, which in turn reduced their overall coverage ratio. As vessels become progressively thinner with increasing distance from the umbilical cord, their surface features get fainter and they start to blend in with scanning artifacts. Having less experience with placental vessel trees, most participants therefore stopped tracing early.

Some branches of the vascular tree were identified only by a subset of participants. We identified two reasons that multiple participants missed blood vessels. Several vessel branches in the lower left and lower right of the vascular tree showed comparatively faint features that were frequently overlooked. Additionally, the arcing blood vessel on the top right was reportedly difficult to identify because it followed the wall of the placenta perpendicular to the rest of the mostly planar vessel structure, making it more challenging to spot from our standard viewing position.

Beyond the reference dataset, we found that most participants marked supposed additional blood vessels around the central umbilical cord. False-positive annotations to the top left of the umbilical cord center (Figures 8.c, 8.d and 8.f) can be attributed to an artifact in our visualization. To give participants a sense of scale, we superimposed a 3D grid over the visualization, creating raster outlines and isolines as seen in Figure 6. The incorrectly marked vessels coincide with an isoline at the same location and have most likely been misidentified. Likewise, several participants misidentified a vessel right below the umbilical cord that is located at one of the visual artifacts created by the segmentation and removal of the fetus.

Apart from these two common areas, each participant annotated individual additional vessels, sometimes tracing vessels farther than the expert and other times marking regions not considered

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in the reference data. However, most of these remaining annotations are in areas relatively far from the umbilical cord, making misidentifications more likely.

The completion time for each tracing task varied greatly among participants and correlated weakly with the number of placed line segments (Table 1). Since no time limit was imposed, some participants spent more time exploring details of the dataset mainly during the first trial.

Table 1. Quantitative results for participant performance

| Participant | # of Segments | Precision | Sensitivity | Average Time |
|---|---|---|---|---|
| 1 | 83 | 91.5% | 48.6% | 207s |
| 2 | 98 | 74.5% | 44.6% | 235s |
| 3 | 179 | 59.8% | 38.3% | 274s |
| 4 | 161 | 85.1% | 52.0% | 384s |
| 5 | 130 | 75.4% | 67.1% | 419s |
| 6 | 105 | 65.7% | 68.5% | 301s |
| 7 | 244 | 79.9% | 85.2% | 557s |
| 8 | 166 | 79.52% | 66.1% | 338s |

## User Interaction

Analyzing video recordings and positional data of tracking data, we found that participants remained relatively stationary during the tracing task. On average, user head positions varied by 0.3, 1.2, and 0.7 m along the X, Y, and Z axes, respectively, relative to the dataset in real-world coordinates. This shows that participants did not make full use of the horizontal space the VR environment offered. We believe that this was caused by our method for placing annotation marks. To place line segments accurately, participants had to keep the wand in a stable position while moving their head to benefit from the parallax effect in VR. This is feasible when stepping forward, backward and while crouching, but more difficult when stepping to the side. We also report that participants rarely used the wand to rotate or translate the dataset and deduce that they deemed the default orientation good enough to solve the annotation task.

Figure 9 shows an example participant tracing from one trial along with lines indicating where the participant’s head was as each segment was drawn. These segments are shown along with a representation of the front screen of the YURT to give an idea of the space.

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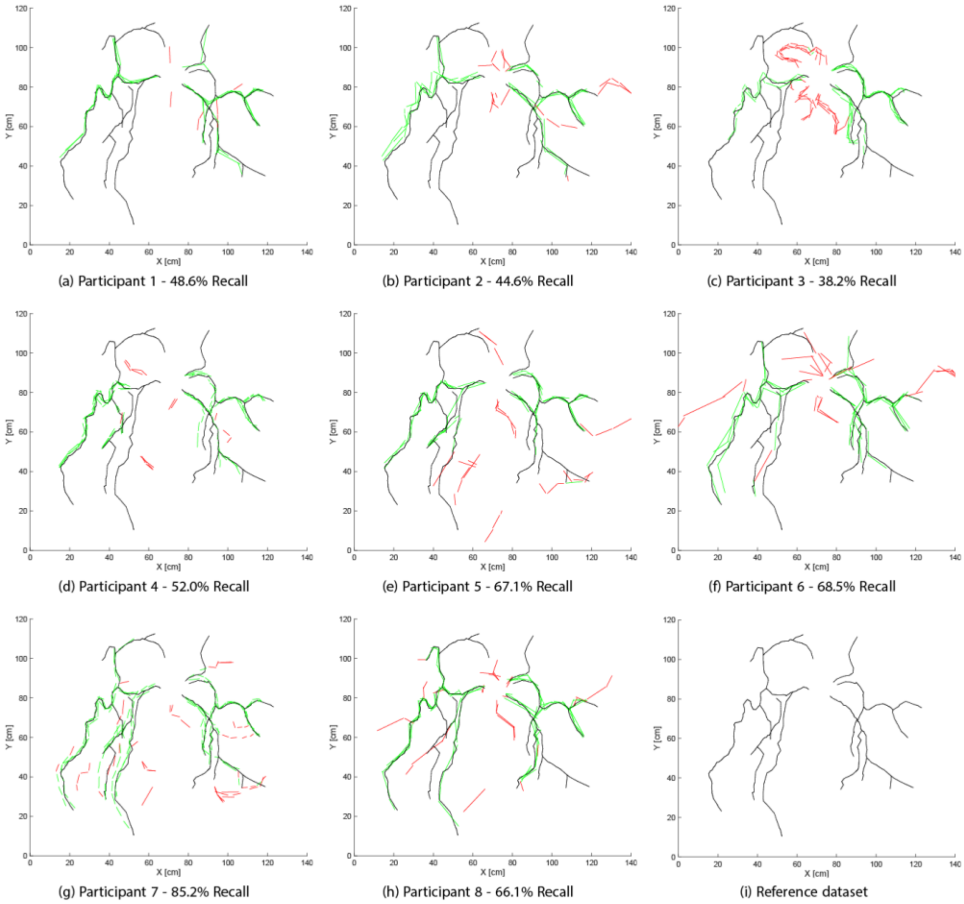


Figure 8. Comparison of segments drawn across all eight participants; each plot is labeled by participant number and all three trials from that participant are overlaid. The expert reference is shown in black; segments with projections within 2 mm of the expert reference are green, and segments outside that area are red. Each plot shows the original user input without projection. Some green lines appear to be offset from the reference tracing; however, projecting them to the surface from their head position places them within the error margin. Tracings of participant 6 (f) were trimmed in this figure to match the scale of all plots, the full extent of false positive tracings can be seen in Figure 7.

# DISCUSSION

In the context of the field of expertise of our medical collaborator, TTTS intervention, the study was an effective proof-of-concept. Participants were able to reliably identify blood vessels of 1 mm diameter, well within the vessel size targeted at surgical TTTS interventions. Additionally, they did this in an MRI dataset in which manual and automated vessel segmentation methods were not producing satisfactory results. This study is a first step towards using MRI visualizations to analyze placental vasculature without the use of a contrast agent.

Both expert and all participants agreed that the ability to view the entire dataset at large scale in VR is a major advantage over more confined views in desktop environments. However, during the experiment we identified several topics that need fuller discussion.

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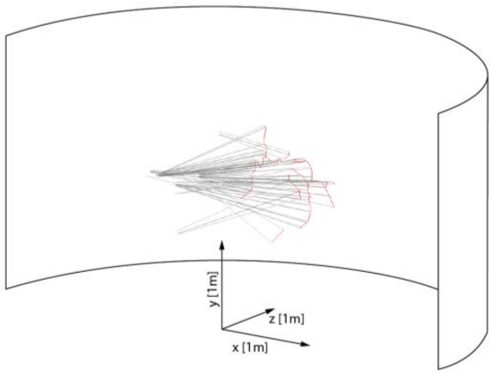


Figure 9. Example results from a single trial showing the tracing segments in red and the head-wand vectors in gray surrounded by a representation of the YURT screen.}

## User Interaction Methods

We found that an actual analysis and planning application in VR would need to consider some of our results. With the interaction tools currently available, participants in our study could not reliably keep their vessel annotations on the placental surface. As pointed out by Keefe et al.[7], drawing on air is difficult; this is also true of precisely placing endpoints of 3D line segments. While some of this can be explained by the participants' brief learning period and their inexperience with 3D VR interactions without haptic feedback, we suggest that the interaction tool should assist users in this task.

We see two ways of extending our current method to address this problem. First, modern VR controllers often include vibration motors to provide haptic feedback. Using this standard method would allow us to notify users whether they are currently touching the placental surface with the wand tool, in addition to visual feedback like highlighting the wand marker. The other option would be to use a ray interaction tool, like a virtual laser pointer, to interact with the data. This would let users point to the placental surface and have annotations snap to the intersection point between surface and ray. Similar ray-based selection techniques have already been demonstrated by Wiebel et al.[8]. This method would allow users to step away from the dataset and use the full available space in the VR system to analyze the data while still letting them complete annotation tasks, but it would require more training to be used effectively.

## Generalizing VR Environments

In this experiment we used the YURT as our base VR environment due to its high visual fidelity. Current consumer-grade VR systems, like the HTC Vive or the Oculus Rift, provide significantly lower resolution and field of view. The transfer of results between VR systems is an active research problem, and it is currently uncertain whether specific benefits can be transferred between different VR platforms. However, based on the interview feedback we gathered from study participants, one of the core benefits they see in this system is the ability to show a dataset at large scale and explore it with an intuitive way to select viewing positions. Most current HMD and CAVE systems can reproduce such an experience, and this strengthens our belief that our results can be applied to other available VR technology.

## Applications

Our study participants commented on the potential benefits of this system in areas beyond TTTS intervention. One participant remarked that the technology might be useful in helping neurosurgeons find aneurysms, and another indicated that the same kind of visualization could help in facial reconstruction surgery by showing the surgeon a patient's anatomy in a noninvasive way.

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Additionally, participants also stated that this technology could be invaluable in education, whether in training surgeons by simulating the precision of movement required for endoscopic surgery or in educating students about the anatomy of the placenta or other parts of the human body. A recent overview paper by Olasky et al. shows that surgical training in VR is indeed a very active research area[9].

## CONCLUSION

We presented a case study evaluating our virtual reality system in finding placental surface blood vessels using a VR visualization of MRI data. We found that medical professionals can accurately identify relevant vessels of 1 mm diameter in our experimental VR visualization, a task critical to the treatment of placental diseases like twin-to-twin transfusion syndrome. Most participants achieved a tracing precision greater than 75% when evaluated against the expert reference tracing, with a lower bound of 59.8%. Our findings underline the importance of large-scale VR MRI visualizations, since we were able to visualize vessels in a scan taken without the use of a contrast agent.

On the level of user interactions, we found that study participants had difficulties placing annotations at the correct 3D depth within the VR environment. The recorded annotations exhibited view dependency: i.e., they appear in the intended location when viewed from the head position at drawing time but show depth deviation when viewed from any other point. This underlines the difficulty of 3D tracing based on visual cues without haptic touch feedback and the need for interaction methods that support users in this task. We report our insights into the VR interaction methods required to create effective immersive medical visualization applications.

Finally, interview feedback from study participants showed that the annotations generated in our experimental system can be helpful in analyzing and discussing individual vascular structures. Our application is a step towards a surgical planning VR environment for TTTS intervention.

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