Exploring Needs and Design Opportunities for Virtual Reality-based Contour Delineations of Medical Structures

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ABSTRACT

Contour delineation, a critical phase in radiotherapy planning, refers to the process of identifying and segmenting malignant tumors and/or healthy organs from medical images. Today's contouring software requires oncologists to inspect and contour target of interests by analyzing a stack of planar medical images, which is lengthy, tedious and sometimes error prone. Such design is also in contrast to the stereoscopic nature of medical images. Therefore, it is intuitive to consider bringing contouring into immersive Virtual Reality (VR) space. We present an exploratory study that uses iterative design to understand needs and opportunities to bring contour delineation into an immersive 3D space, such as the one enabled by today's head-mounted VR displays. We report on the interactions with three medical professionals and three engineering & design experts, and demonstrate the potential for VR–based 3D contouring while studying the benefits of using 3D immersive spaces to augment the process of contour in 2D. Through needs–finding interviews and co–design workshops, we evaluated our initial iterations and proof–of–concept prototypes. We believe that our preliminary findings will benefit researchers and practitioners who are attempting to bring today's contour delineation processes into an immersive 3D space.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**.

KEYWORDS

Virtual Reality Applications, Radiotherapy Treatment Planning, Oncology, Contour Delineations

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1 INTRODUCTION

Radiotherapy (RT) Treatment plays an important role in cancer management. Contour delineation is a critical step in RT workflow where practicing oncologists identify and outline malignant tumors and/or healthy organs from a stack of medical images. Inaccurate contouring could lead to systematic errors throughout the entire treatment course, leading to either miss the malignant tumors, or over–treat the healthy tissues [35]. From the patient's side, poor contouring could cause increased risks of toxicity, tumor recurrence and death. For example, existing works show a significant decreasing of survival rate in head–and–neck cancer [24, 33] due to the violation of contouring protocol.

To enhance contour performance, professional desktop based software packages, *e.g.,* Eclipse [30], have been introduced, where practicing oncologists could explore and contour 3D structures by analyzing a stack of planar medical images, while typically being constrained to only work with 2D displays (see Figure 1b). Although

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radiation oncologists are trained to work in the 2D space, mentally reconstructing stereoscopic physiological structures still introduces increased cognitive load during the medical image analysis process [15], and could introduce additional time due to the slice–wise nature of contouring 3D structures in 2D.

3D immersive experience in Virtual Reality (VR) have unlocked a variety of applications, from those facing toward general users (*e.g.,* teleconferencing [9]), to healthcare domain experts (*e.g.,* telesurgery [11–13]). "Radiation oncology integration", in particular, has been advocated as a target healthcare application in VR [6, 17, 32]. Such value has been widely recognized since Hubbold *et al.* [16] built the first stereoscopic displays for visualizing radiation treatment plans. While existing works have evaluated the affordances of VR while being applied to visualizing the treatment plans [23, 29] and enhance understanding of dose distributions [25], 3D contour delineation, as the initial phase of the workflow, is less explored. Few recent works such as DICOM VR [22] and Elucis [19] attempted to bring radiation planning procedures into VR-based immersive 3D user interfaces, however the lack of ways to enable radiation oncologists to continue refining drawn contours, hinders the practical uses. While Williams *et al.* [32] showed 83% of oncologist participants found it useful to use VR for visualizing and contouring medical images, it is still unclear what affordances of the VR system can really impact contouring.

To address this open question, we used a domain–expert–centered iterative design approach and worked with three medical professionals and three engineering/design experts, to create an initial prototype of a VR system for 3D contouring. This paper presents our ongoing research and initial insights that outlines multiple key affordances that a VR system can bring to contour delineation process. We also report on the results of an initial usability evaluation of the final prototype with domain experts from *an Anonymous Academic Medical Center*. We believe that our work will benefit researchers and practitioners who are working on designing VR based software supports for future radiation oncology.

2 BACKGROUND AND RELATED WORK

2.1 Contour Delineation in Radiotherapy Treatment (RT) Planning

Contouring is a critical and indispensable step in the RT process [8]. The overall contouring process is shown in Figure 1. Its ultimate goal is to deliver high doses of radiation to a tumor, while limiting the dose that is received by the surrounding tissue. To accomplish this, the radiation oncology team—typically involving a radiation oncologist, a physicist and a dosimetrist—needs to interpret CT scan images (MRI and PET if needed) to recreate a "virtual anatomy" of the patient and locate malignant tumors.

Commercially available computer supported software, *e.g.,* Eclipse [30], are widely used in today's hospital to streamline and accelerate this process. Such tools allow users to easily register and align each slice of DICOM images, generated by scanning instruments, and drawing annotation traces precisely using general input tools, *e.g.,* mouse and stylus (see Figure 1). Advanced features, *e.g.,* inter–slice interpolations [1, 37] are also widely used to reduce the number slices to be manually contoured for less rapid changed structures.

Despite the availability of these tools, the contouring procedure is still a lengthy process, as the oncologists need to examine each slice and annotate the target tumoral volume while distinguishing it from healthy tissue [10, 31]. It is also error prone since the oncologists need to mentally reconstruct the medical structure by looking at a stack of planar scans in order identify the locations of the target volume. For instance, an early study showed how nine participants invited to contour target volumes on spinal canal and lungs, using 2D contouring system with mouse and a lightpen, introduced more than 30% of errors [10].

Some existing works attempted to address this challenge by realizing the paradigm of "auto–contouring". For example, Nikolov *et al.* [20] demonstrated a novel 3D U-Net architecture that could achieve expert–level performance while delineating 21 distinct head–and–neck target commonly segmented in clinical practice. While AI-assisted contouring can effectively empower clinicians beyond their current practices [35], there is a high cost associated to false positives and negatives in this domain. In addition, to support effective AI-approaches, large datasets are required and the limited availability of those large datasets impacts the scalability of applying AI to contouring.

In contrast, we think that new immersive and 3D visualization technology can effectively help radiation oncologist during their contouring practices, without replacing their judgement. We are therefore investigating the merits of immersive 3D user interfaces powered by commercially available VR systems, and exploring how participants could gather a "bird–eye view" of medical scanning and interact with the tumoral target directly in 3D.

2.2 Virtual Reality in Radiation Oncology

Virtual Reality (VR) refers to the paradigm where computing technology could be used to create a 3D simulated environment. The paradigms of VR has been well realized by a wide variety of affordable and commercially available VR headset, like the most recent Quest 2 [26]. Together with Augmented Reality (AR), VR has been advocated as the next frontier for a wide variety of healthcare and health science practices [3], and a wide variety of related work has explored the affordances of immersive 3D visualization of medical structure powered by commercial AR/VR headsets (*e.g.,* Anatomy Studio [36]).

Boejen *et al.* [6, 29] summarized how VR could benefit today's radiation therapy training by enabling students to simulate and train clinical situations without interfering practical clinical workflow and without the risks of making errors. Instead of focusing on training of clinical skills, Patel *et al.* [23] designed a VR system to evaluate RT plans. They showed how the stereoscopic visualization could foster the understanding of spatial relationships between patients' anatomy and calculated dose distributions.

Williams *et al.* [32] also pointed out that 3D volumetric rendering could be particularly advantageous when the definition of clinical target volume is based on 3D spread of disease along anatomical features with intricate topology. Such volumes could be difficult to observe and evaluate as they usually do not lie neatly in any of the traditional saggital, transverse and frontal planes [32]. With such motivations, they designed DICOM VR [22] a system that allows radiation oncologists to manually delineate the target volume

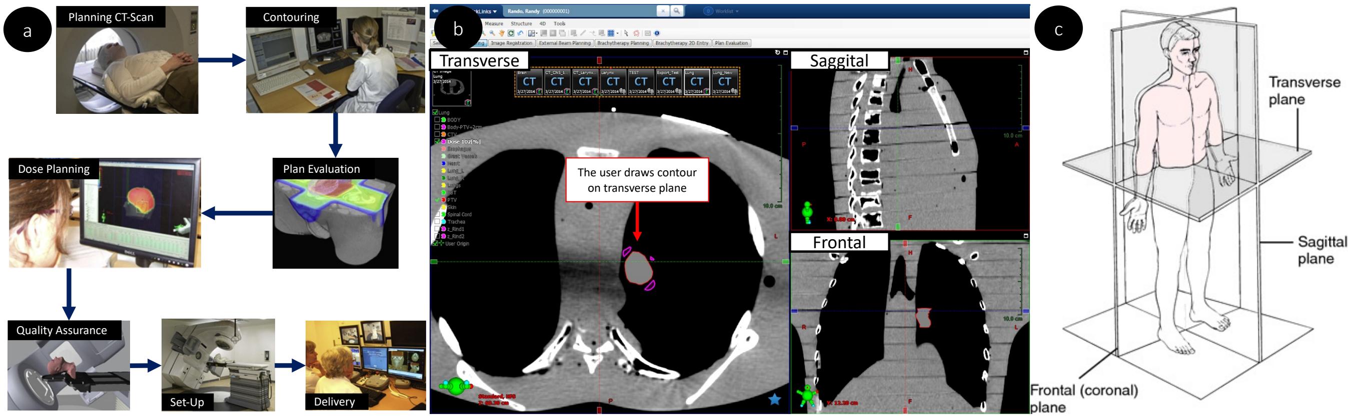

Figure 1: Example workflow and contour interface for 2D display grounded computer. (a) Workflow of today's RT: our work is focusing on the "contouring" phase (the demonstrative figure is revised from [6]); (b) Main contour delineation interface of Eclipse [30], with practicing oncologists exploring different slices by scrolling the mouse and contour on transverse plane; (c) Demonstrative figures of three images planes with respect to the body position;

directly in 3D space. Early results of using this system show that while the contouring line seems to be reduced compared to 2D display based software, the drawing precision might be sacrificed to some extent [32]. Although 83% of participants who are practicing oncologists found DICOM VR useful [32], we believe that the underlying affordances are still unexplored and more work is needed to really understand how to best support this process in a 3D immersive environment.

In our work we aim to understand how VR and 3D immersion can benefit the contour delineation process, and how to design such a spatial system by fully exploiting the affordances that this medium offers in this specific context. In this paper, we report on our initial need finding activity, directly involving domain experts in health science and engineering, and on an initial proof–of–concept prototype design, including a first iteration of usability evaluations.

3 METHODS

3.1 Participant Recruitment

Our study was rooted in the participant observation methodology [28] and involved a total of six participants (see Figure 2). Three participants are health science domain experts, recruited from UC San Diego Health System at different levels of experience (including MD student, residents and attending physicians). The other three participants came from the engineering and interaction design community.

We selected a participant-observation method for this particular study since we believe that performing activities with the target group (radiation oncologists) gave us greater empathy, as well as a much more in-depth understanding of their activities. The study was approved by the Institutional Review Board (IRB).

3.2 Procedures

We used an iterative design process [21, 34] to investigate and surface domain experts' needs. We used thematic analysis [7] to examine the approximately two hours of video/audio data.

[Phase 1]: *Needs Finding*— While contour delineation of medical images is an advanced skill, often trained during medical residency, that requires solid knowledge in both human anatomy as well as medical images interpretations, junior medical school students are usually introduced with such knowledge during the introductory course works [4]. Our needs finding aims to capture the perspective of both novices and experts. We interviewed P1, a medical student who has been trained through human anatomy courses, yet unfamiliar with practical contouring procedures. Despite this, the high level concepts learned in anatomy are related and have been introduced in the past courses. We also interviewed P2 and P3, a senior resident fellow and practicing oncologist in radiation oncology being experienced in human anatomy and medical images interpretation. Since all domain experts have never used VR in the past, we first introduced basic concepts and showed some existing VR based medical image visualization applications to help the subsequent ideation process. Our individual need finding semi-structured interviews focused on two guiding questions:

- *What are the potential benefits that VR could bring to today's contour delineations procedure?*
- *What are possible features that might be particularly useful to augment today's contour process in 3D?*

[Phase 2]: *Co–Design Workshop and Initial Prototype Evaluation.*— We engaged P2–P6 to participate in a co-design session that focused on the use of "3D output" (*i.e.,* how helpful a stereoscopic volumetric rendering could be for augmenting the contouring experience?) and for "3D *vs.* 2D input" (*i.e.,* what input modality would be more useful, and how can 2D and 3D inputs be potentially combined?). The co–design cohort included three expert designers, and two domain experts in radiation oncology field. P1 was excluded from this phase, due to the lack of practical contouring experience.

4 NEED FINDING RESULTS

We first report in this section on the outcome of our needs–finding work, and discuss the application of the outlined themes to design and develop a first prototype as shown in the next section.

Index	Gender	Professional Field	Level of Experience	VR Experience	Iteration 0	Iteration 1
P1	F	General Healthcare	Junior medical student.	Never used VR	X	
P2	M	Radiation Oncology	Radiation oncology fellow.	Never used VR	X	X
P3	M	Radiation Oncology	Practicing oncologist and radiation oncology faculty.	Never used VR		X
P4	M	Engineering & Design	Doctorate student in engineering and design.	Has tried VR few times		X
P5	M	Engineering & Design	Faculty in engineering and design.	Expert in VR		X
P6	M	Engineering & Design	Faculty in engineering and design.	Expert in VR		X

Figure 2: Recruited participants for initial need finding study. Notably, we consider P1 – P3 as the domain experts with different levels of experience highlighted, whereas P4 – P6 are professionals in the engineering and design community.

Identifying and annotating key structures from 2D medical images is challenging and tedious—While it is possible to identify planar medical images after years of training, participants agreed that learning such skills are challenging to learn (*e.g., "I'm very comfortable with [interpreting] 2D anatomy. But that was hard to learn!"* [P2]). P1 emphasized that identifying targets from planar medical images is what a typical medical student needs to learn in the first year: *"We begin seeing a little bit of [organs from medical images] in the first year. Because that's part of our anatomy class."* P1 also commented on the 2D medical image interpretation skills of a typical junior medical student: *"Bigger structures like big organs, liver and stomach, even the pancreas, probably yes [can be easily identified from planar images]. But things like vasculature can be harder to identify."*

To identify key targets, participants emphasized the process of mentally reconstructing medical structures by looking at adjacent slices and different oriented cutting–planes: *"You get a stack [of planar medical images]. And then you can go [back and forth], and change the different [cutting plane] to see where you are. [...]. We don't get to see only one image. You can go up and down and then kind of orient yourself in."*

The feature of *inter–slice interpolation*, where the underlying morphology based algorithm (*e.g.,* [1, 38]) outlines the contours by looking at users' drawn contours on two non-adjacent parallel cutting planes [14] is provided by many of today's contouring software to accelerate such process. Participants outlined the importance of using such features to reduce the lead–time of practical contouring. For example, *"With the bladder, I might do [use the interpolation] like every 3rd slice. But that'll be different for the lungs. The lungs are a vertically big organ. So it probably appears over a 150 slice range. It also depends how thick your slices are. So you might have to contour more just to get the whole thing."* [P2].

While selecting cutting planes to manually draw contours, P2 explained the importance of considering "how rapid the organs are changing" by examining the stack of slices. However, such process could still be tedious for some critical organ: *"If it's like a simple homogeneous organ that's not changing rapidly, maybe it will be [selecting slice manually] every 4th, [or] every 5th slice. I don't think I would ever do more than every 5th. If it is a very critical organ like a tumor, and it's hard to see and the changes in shape, then you're doing every other, potentially every slices although that gets really tedious."* [P2] This echos general guidance for contouring large structure, where every other slices are recommended [14].

Viewing medical structure directly in 3D might benefit 2D medical image interpretations—After having been introduced to the concept of VR and having seen some examples of volumetric rendering of DICOM files[1], participants mentioned that having a stereoscopic visualizations of medical structure could be extremely helpful for learning (*e.g., "[...] when I first took my anatomy class, I would have loved to see a 3D volume in VR"* [P2]). Participants also mentioned the potential two benefits for practical contouring practice:

(1) Overall View: Having an "overall view" of medical structures could be helpful on determining the boundary between normal tissues and malignant tumors. For example, *"I know there's a cancer, here at the edge of the pancreas, and often what you're trying to do is decide where does that cancer stop? Where do I want the radiation to go? And then, [identifying the normal tissues], this looks like a normal structure. You can imagine that sometimes is not easy. So, being able to visualize everything in 3D, it could help you see those borders better."* [P2].

(2) Flexible Orientation: Having flexibility of placing and orienting cutting planes might be helpful for examining targets and for the subsequent inter-slice interpolation. P2 provided three examples based on his residency experience:

(i) *"There are scans like the rectal MRIs, where they will reconstruct the images in an angled plane that is not strictly central frontal. Because of that, it's easier to visualize anatomy in that plane. So if you could switch into that plane and contour on it, that may be better. It's not something I've ever used, but some clinicians conjure software to have ways of switching the plane."*

(ii) *"[The uterus flaps around, sometimes it'll look like some of the things like this [showing one angle] and things like that [showing another angle]. So if you were able to see whatever ways it's angling, that would be helpful."*

(iii) *"Blood vessel ... it's harder to just scroll back and forth on this where I don't even have transverse planes to refer to . But I could*

[1] DICOM (Digital Imaging and Communications in Medicine) files are the standard file format for the communication and management of medical imaging information and related data. In our study, each DICOM file contains the image data of a cross–sectional slice of the CT scanning.

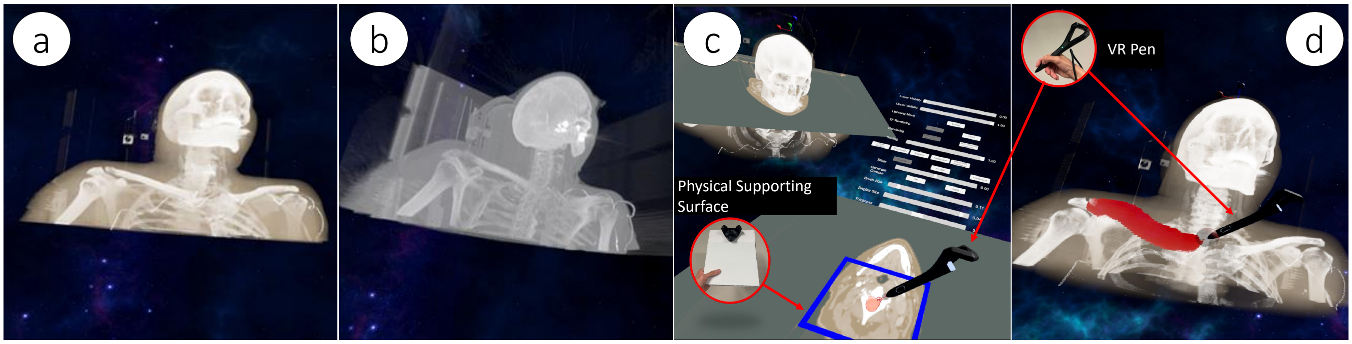

Figure 3: Example scenes and workflows of contour delineation in VR. (a) Direct volume rendering; (b) Maximum intensity projections; (c) Example 2D contouring with VR pen and tablet; (d) Example 3D contouring with 3D brush. The example head–neck structure was rendered from DICOM dataset used in eContour [27].

> *look back and forth at the sagittal and the 2D...in the 2D, you see a fastball in the sagittal. And you're trying to figure out if that's the same thing that you're looking at, in the transverse plane."*

Inspecting in 3D might be helpful, yet preserving the ability to contour in 2D is critical—Finally, participants believed that instead of removing the 2D contouring completely, it might be more reasonable to use 3D volumetric rendering to augment the 2D contouring: *"We're very familiar with the 2D transverse because that's what all the diagnostic scans that we look at [show], including all the CTs, PETs, and MRIs."* [P2]. P2 provided also some insightful thoughts from the clinical perspective: *"It's going to be a back and forth process [looking at a stack of slices] at the end of the day, where you can still keep doing your 2D annotations, or the contouring. But then at some point you need, or maybe you don't need it, but it makes sense to have a 3D representation and do some of these in 3D."*

5 INITIAL DESIGN AND PROTOTYPING

Building on our need findings, we implemented an initial proof–of–concept prototype on HTC Vive Pro, using Unity (V2020.3.6f1) and SteamVR SDK (V1.14). Three SteamVR base station (V2.0) were used to reduce tracking inaccuracies. We started our iterative development by prototyping initial features based on participants' emphasis.

Cross-Dimensional Contouring, and Pen+Virtual Tablet Interactions—While controllers are the most fundamental and popular tools for mainstream VR applications, we chose to use the Logitech VR stylus [18] as the input tool for 3D contouring due to the advantages of drawing precision [2]. In addition, instead of completely removing 2D contouring, our design allowed radiation oncologists to draw 2D contours on a virtual tablet where a cutting plane would be mirrored (see Figure 3c). A physical foam board, equipped with a tracker, is aligned with the virtual tablet, offering participants physical support to maximize drawing accuracy [2]. During the study, participants could switch contouring between 2D and 3D based on their own preference. Independently of their choice, all contour traces were visualized in both the 2D and 3D spaces (see Figure 3c and d).

Adjusting Rendering Parameters—Since contouring requires participants to see structure inside 3D volumes, we decided on using a semi–transparent volumetric rendering algorithm. In our prototype, we used direct volume rendering and maximum intensity projection algorithm to render the input DICOM files (see Figure 3a and b). Participants were provided flexibility to adjust intensity and position (*i.e.,* translation, rotation and scaling) of the target medical structure.

Selecting Optimal Cutting Planes—Since we want to preserve 2D contouring, participants were provided flexibility to select the optimal orientations of the cutting plane (*i.e.,* saggital, transverse, or cofrontal). To allow for this flexibility, the cross-sectional images of the selected cutting plane was be mirrored on the handheld virtual tablet, on which participants could refine the contours as needed.

Varying Size of Input Tools—Due to the needs for annotating fine–grained tissues, we also provided participants flexibility to change the size of draw brushes, and the tablet. When varying the size of the tablet, a virtual blue rectangle would still highlight the physical supporting board (see Figure 3c).

6 CO–DESIGN WORKSHOP AND INITIAL PROTOTYPE EVALUATION

After having developed our first prototype gather some initial feedback, that we distill here in three main points.

Viewing and drawing medical structures in 3D is helpful, yet it lacks fine-grained views of soft tissues—Both domain expert participants agreed that directly inspecting 3D medical structure could be helpful for identifying hard tissues (*e.g.,* bones and teeth), but it might be less helpful for soft tissues: (*e.g., "You can see the bones extremely clearly. It'll help orient ourselves in the body. But in terms of drawing some of the finer soft tissues...I'm not sure how that would work"* [P2] and *"If we could figure out a way to show the structures that we want to show, that could be helpful [...] to look at the course of a muscle in a river of blood vessel and see where it's deviating ... might be helpful."* [P3]).

P2 also appreciated the flexibility of 3D brushes: *"I like that I could draw [on top of] an eyeball, a perfectly spherical structure with* *a perfectly spherical 3D brush. It's like one click versus ... if you're doing this on axial images."* [P2].

When asked about their experience contouring in both 2D and 3D, two participants confirmed that supporting contour delineation on both spaces might be helpful in some cases. For example, P3 mentioned how *"as you're drawing in 2D, you can see a 3D rendering of a structure [...] that actually could be a really interesting concept and might improve contouring accuracy. To really see the structure, like a prostate cancer, being able to see the course of the rectum, see where the prostate sits, see how the seminal vesicles go over [...] and kind of understand that anatomy, and actually see that 3D, that actually might result in more accurate contouring, especially for people that are just learning."* [P3]. Similar ideas were also echoed by P5: *"One possible process would be look at the 3D structure to understand the anatomy, and then see the connections with the 2D image by going back and forth. And then do your contouring on your 2D interface, but at the same time, see how this reflects back to the anatomy. So you kind of have the whole picture"* [P5]

Considerations for learning 3D user interface are needed— Participants also believed the learning efforts are important to be taken into considerations, because *"the rest of our world is so grounded in 2D."* [P2]. While the anatomical structures data comes in 3D by nature, today's healthcare system requires participants to learn, interpret, and annotate such data in 2D, leading to the fact that participants feel more comfortable to analysis medical structure in 2D, rather than 3D. For example, *"We work with 2D images, but have to think in 3D. It's a little bit of a paradox."* [P3] and *"No doctor will ever see it as 3D. We're always scrolling the plane, [...] but it's always on 2D."* [P2] While domain experts participants took on average 10 min to get used to the VR system, P2 believed that learning time and efforts for general radiation oncologists would not impact usability: *"I don't think it would take that long, like a couple hours just to get used to pushing the buttons ... finding the buttons on the pen was hard for me."*

Rendering 3D structure with visual references based on different needs—Due to the additional information delivered in 3D, participants believed that more visual cues and references, as well as fundamental volume characteristics were needed. P3 provided examples in terms of examining image symmetries: *"What we're looking for are really subtle contrast differences [..] There are times when we have two things that are supposed to be symmetric, and then one is much bigger."* [P3]. Participants also agreed on the usefulness of semi-transparent volumetric rendering after initial trials. While the 2D images are not transparent, being on a plane they do not present any visual occlusion. In 3D, participants confirmed that our approach towards semi-transparent rendering was needed, because it allowed them to easily see structures inside the body and identify them easily as targets to be contoured: *"I think it's necessary [to be semi-transparent] [...] because everything we contour is on the inside."* [P2]

7 CONCLUSION AND FUTURE WORKS

In this paper, we presented our on–going work and initial findings of a domain–expert–centered iterative design approach to understand the potential affordances that the VR system could bring to contour delineation process. We demonstrated that 3D immersive (VR) contouring shows promise and paves important motivations for using 3D immersive space to augment the contour delineations processes. We also believe that while our main focus is radiation oncology, our findings can be generalized to other specialities like for example surgical planning [5].

Our findings also clarify two aspects of future works. *First*, while this initial work allowed us to sucessfully go through the first iteration of our design, we see a great opportunity to create novel interactions that could address multiple concerns raised by our participants (*e.g.,* create new ways to enable domain experts to inspect the details of soft fine grained tissues). *Second*, we plan to conduct more in-depth quantitative and qualitative evaluations, with both practicing oncologists and medical students, of our system as we proceed through the next iterations. We would also like to increase the diversity of our participants, and recruit them from a range of medical centers.

All in all, we believe that our initial findings will benefit future researchers and practitioners who are attempting to bring today's contour delineation processes into VR immersive spaces.

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