Report Number: wucse-2009-13

2009

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Ross Sowell, Lu Liu, Tao Ju, Cindy Grimm, Christopher Abraham, Garima Gokhroo, and D Low

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Type of Report: Other

pp. 1–9

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Abstract

*Recent advances in surface reconstruction algorithms [BM07, LBD*08] allow surfaces to be built from contours lying on non-parallel planes. Such algorithms allow users to construct surfaces of similar quality more efficiently by using a small set of oblique contours, rather than many parallel contours. However, current medical imaging systems do not provide tools for sketching contours on oblique planes. In this paper, we take the first steps towards bridging the gap between the new surface reconstruction technologies and putting those methods to use in practice. We develop a novel interface for modeling surfaces from volume data by allowing the user to sketch contours on arbitrarily oriented cross-sections of the volume, and we examine the users' ability to contour the same structures using oblique cross-sections with similar consistency as they can using parallel cross-sections. We measure the inter-observer and intra-observer variability of trained physicians contouring on oblique cross-sections of real patient data as compared to the traditional parallel cross-sections, and show that the variation is much higher for oblique contouring. We then show that this variability can be greatly reduced by integrating a collection of training images into the interface.*

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Modeling packages I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques
General Terms: Design, Experimentation, Human Factors
Additional Key Words and Phrases: User interfaces, user studies, oblique contouring, sketching, volume graphics, segmentation, surface modeling

1. Introduction

Magnetic resonance imaging (MRI) and computed tomography (CT) scanners have long been used to produce three-dimensional samplings of anatomy elements for use in medical visualization and analysis. From such datasets, physicians often need to construct surfaces representing the anatomical shape in order to conduct treatment, such as radiating a tumor. Traditionally, this is done by a time-consuming process in which an experienced scientist or physician marks a series of parallel contours that outline the object of interest.

The recent work of [BM07,LBD*08] provides algorithms for reconstructing a surface from contours drawn on non-parallel planes that could greatly reduce the manual component of this process (see Figure 1). However, current medical imaging systems do not provide tools for sketching contours on oblique planes. In this paper, we take the first steps towards bridging the gap between the new surface reconstruction technologies and putting those methods to use in practice. In conjunction with a group of radiation oncologists, we investigate the feasibility of oblique contouring. We develop a novel sketch-based interface that allows the user to generate a surface from just a few contours drawn on arbitrarily oriented planes. The user can then review and edit the model globally and interactively, rather than marking many parallel contours on a slice-by-slice basis.

If this technology is to be adopted in practice, it is not enough to simply build an oblique contouring tool. We must also measure the ability of the users to produce surface models of similar quality by using a small number of oblique

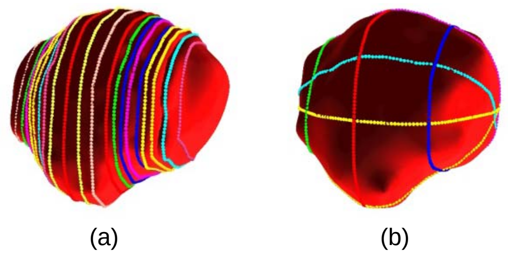


Figure 1: *Surface models models of a human prostate, reconstructed by our system using (a) 20 parallel contours (b) 7 oblique contours. We believe that the efficiency of the contouring process can be improved by using a small set of oblique contours rather than many parallel contours.*

contours, rather than many parallel contours. However, the act of marking these contours is not a trivial process that amounts to tracing clear edges in the image. Instead, the user must often rely on subtle cues in the image data (see Figure 3) to identify the boundary of the structure. Therefore, an important first step in this process is to show that users are able to contour the same structures with similar consistency using oblique cross-sections as they do with parallel cross-sections. We measure the inter-observer and intra-observer variability of physicians contouring on oblique image planes as compared to the parallel case and find that the variation is much higher for oblique contouring. We then show how the consistency is greatly improved by integrating a collection of training images into the interface.

The main contributions of this paper are:

- A novel interface for modeling surfaces from volume data by allowing the user to sketch contours on arbitrarily-oriented cross-sections of the volume.
- A set of user studies that investigate the feasibility of oblique contouring in practice. Based on these studies, we develop a simple training tool that reduces the variability of oblique contouring, even among novice users.

2. Related Work

2.1. Reconstructing Surfaces from Contours

The earliest approaches to surface reconstruction from contours [Kep75, FKU77] focus on simple closed curves lying on parallel planes and are known as "contour stitching". Many advancements have been made since then, but the basic approach remains the same: connect the vertices of adjacent contours to build a mesh that passes through all the input contours. For a complete review of methods of surface reconstruction from parallel contours, please see the literature review in [LBD*08].

More recently, several methods have been developed for reconstructing surfaces from curves on non-parallel planes [RU90, PT94, WMT*95, DP97, BTS04, BM07, LBD*08]. These methods provide the inspiration for our work, as they make it possible to reconstruct surfaces using just a few oblique planes, rather than many parallel planes. However, current commercial treatment planning systems such as Philips' Pinnacle and Varian's Eclipse do not provide facilities for visualizing or sketching contours on non-transverse image planes. In this paper, we provide the first steps towards bridging the gap between the advancements in surface reconstruction algorithms, and putting those methods into practice in the medical imaging domain.

2.2. Interactive Volume Segmentation

Automatic volume segmentation is a difficult problem because the image data is often noisy and the segmentation is dependent on the subjective interpretation of the observer [ONI05]. Therefore, several interactive techniques have been developed to allow the user to specify input for semi-automatic segmentation. These allow the user to specify constraint points by roughly sketching foreground and background regions on a cross-sectional plane [TLM03] or the volume-rendered image [YZNC05] or by sketching a contour of the region of interest on the volume rendered image [ONI05]. These constraint points are then given as input to a segmentation algorithm that returns a set of voxels inside the region of interest. A surface can then be generated by an isosurface algorithm such as Marching Cubes [LC87]. These techniques allow the user to provide input that guides the auto-segmentation process. Our interface can be used to review and edit surfaces produced using one of these methods, which may be particularly useful anytime the structure does not follow a clear isocontour, or it can be used to build surface models from scratch. Our interface is novel in that it allows the user to sketch contours on oblique image planes and builds a surface that explicitly interpolates those contours.

2.3. Contouring User Studies

Observer variation in contouring structures on transverse image planes has been widely studied in the radiation oncology community [Caz98,Fop03,Wei03], but very few studies have looked at viewing or contouring on non-transverse planes. Steenbakkers et al. [Ste05] found that users who do not reference coronal and sagittal planes have a higher variation in the superior and inferior directions when contouring, and thus have a greater level of inter-observer variation. While no significant improvement in accuracy was measured, Petric et al. [PP08] found that in contouring images for cervix cancer brachytherapy, the contouring difficulty was lower for contouring on paratransverse (perpendicular to the long cervical axis) than in transverse planes. These two studies suggest that in addition to being more efficient, oblique contouring might also be easier and more accurate in some cases. In this paper we present the first studies that examine the ability of

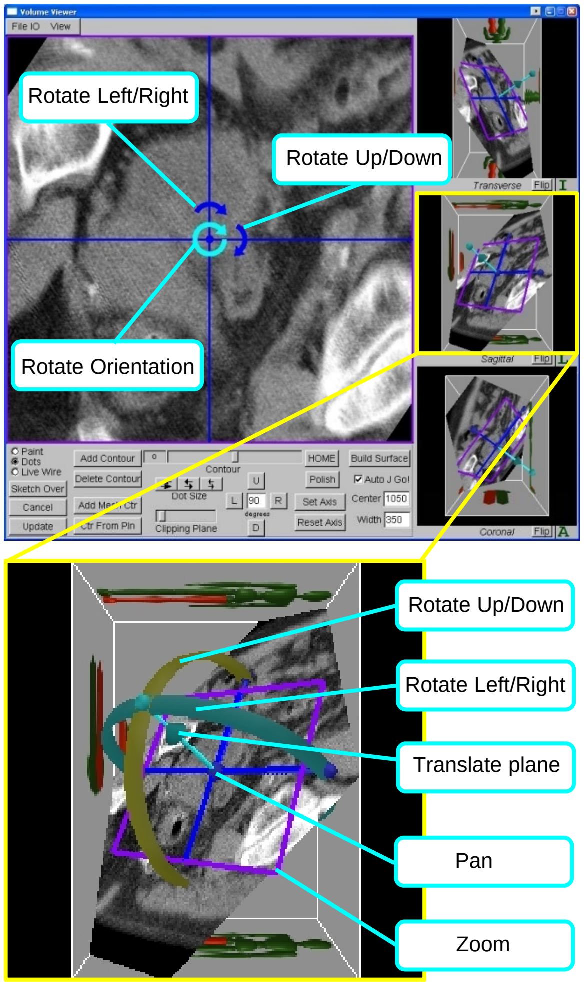


Figure 2: *The VolumeViewer Interface*

users, who have been trained to contour structures on transverse image planes, to contour structures on non-parallel image planes.

3. The VolumeViewer Interface

The VolumeViewer interface is shown in Figure 2 and demonstrated in the accompanying video. In Section 3.1 we describe how the user interacts with the interface, and in Section 3.2 we describe its implementation.

3.1. User Interaction

The interface consists of one large main window and three smaller side windows. Sketching takes place in the main window where the view is always perpendicular to the image plane. The side windows provide fixed views along the three primary axes (transverse, sagittal, and coronal) to help the user maintain an awareness of the current position and orientation of the image plane in the volume. The user's mental model is that the view in the main window corresponds to a camera positioned on the tip of the blue arrow and looking at the purple box in the side windows. A bounding box of the volume is drawn in gray with images of a human model to indicate the patient's orientation with respect to the volume data. This indicates to the user which end of the data is toward the head or feet of the patient, and the right leg of the model is colored red to help the user orient the slice.

From the main window, the user pans the current image plane by clicking and dragging the mouse. The user rotates the plane up or down about its current axis or changes the viewing orientation by using the in-screen arrow controls, and translates the plane along its normal by scrolling the mouse. From the side windows, the user can also adjust the position and orientation of the plane by manipulating a simple transform widget (see Figure 2 (bottom)).

The user can sketch a contour on the current plane by using one of three currently implemented drawing tools. "‘Paint"’ allows the user to contour using a traditional brush stroke. "‘Dots"’ allows the user to click a series of points that are linearly interpolated to form a contour, and we also provide an implementation of "‘LiveWire"’ [MB95] for use when the desired contour follows an image gradient. Contour dots can be removed by pressing the delete key.

Once a set of contours have been drawn, a button can be pressed to build a surface that interpolates the contours. After a surface has been reconstructed, it can be viewed simultaneously with the image data for evaluation. A clipping plane can be turned on to view the intersection of the image plane with the mesh. The mesh can then be edited by modifying existing contours or adding new contours and reconstructing the surface.

3.2. Implementation

The input to our system is a volumetric dataset. The examples in Figure 1 were reconstructed from a 1024x1024x256 CT scan of a human prostate. The data is stored as a 3D texture and any desired smoothing or filtering can be performed in the fragment shader. The system linearly interpolates the data in each slice of the input dataset in order to render arbitrarily oriented image planes. After a set of contours have been drawn using the tools described in Section 3.1, the system reconstructs a surface from the nonparallel contours using the technique of [LBD*08]. This algorithm requires that the contours be closed and that the intersection points along the common line between any two planes be located at the same position. We handle this in a preprocess routine that snaps intersecting contours together so that they share common intersection points. This works well as long as the intersection points are close to one another.

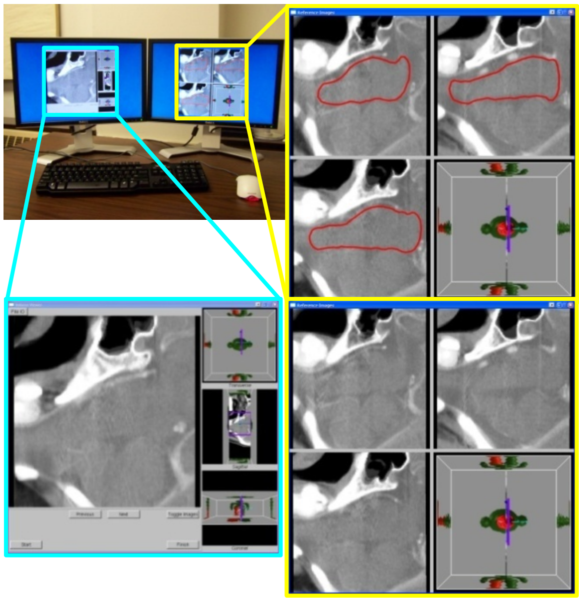


Figure 3: *User study setup. The main window is highlighted in cyan. This is where the drawing takes place, and was the only window available in the first two studies (see Sections 4.1 and 4.2). The window highlighted in yellow contains the reference images, and we show each of the two possible views. The contours can be toggled on (top) or off (bottom) to train the user on cues to look for in the image.*

Case	Comparison	Mean	Overlap
B. Inter	Parallel v. Oblique	0.000	0.000
	Oblique v. w/Ref	0.000	0.000
	Parallel v. w/Ref	0.000	0.049
P. Inter	Parallel v. Oblique	0.000	0.533
	Oblique v. w/Ref	0.000	0.204
	Parallel v. w/Ref	0.111	0.091
B. Intra	Parallel v. Oblique	0.000	0.009
P. Intra	Parallel v. Oblique	0.004	0.082

Table 1: *P-values from Wilcoxon signed ranks tests on the data presented in Figure 4.* $\alpha = 0.017$ *was used as the level of statistical significance.*

4. User Studies

To examine the feasibility of oblique contouring, we conducted two user studies. The main question that we wanted to answer was as follows: Are parallel-plane experienced users able to contour the same structures using oblique planes with similar consistency? A positive answer to this question is required in order for oblique contouring to be adopted in practice.

To investigate this question, we wanted to study how well the users could contour on oblique image planes without other factors influencing the results. Therefore, despite our system's ability to allow the user to navigate the plane in 3D, to show cues from previously drawn contours, or to build surfaces from the contours, we chose not to include those features in this study, in order to simply compare contouring on oblique image planes to the parallel case. In order to take advantage of these more sophisticated features, we first need to verify that our users are able to consistently interpret what they see on the oblique planes.

For these reasons, we made the following restrictions to the interface (see Section 3). Navigation controls were limited to a fixed set of planes. Instead of using the 3D navigation controls, the users were able to move back and forth between the fixed set of planes using Next and Previous buttons. This is the same system that is currently used in treatment planning systems to page back and forth through the slices in the stack. We also chose to only display the contour corresponding to the current image plane. For the oblique planes, we could have also displayed the intersection points of previously drawn contours with the current plane. However, this would have influenced what the user would have drawn and would have caused the order in which the planes were presented to affect the results. Instead, we wanted all users to draw on the same planes with the same information.

A picture of the setup for the user studies is provided in Figure 3. All the participants used identical workstations and contouring tools. They were all required to use the dots method for drawing contours (see Section 3) and were allowed to use the delete key as needed to remove contour dots.

4.1. Inter-observer Variability of Experts

Four radiation oncology residents and one medical dosimetrist segmented ten CT datasets (5 prostate, 5 brainstem) using parallel and oblique methods. All five users had considerable experience segmenting the male pelvis and head-and-neck regions with traditional parallel plane methods. Between eighteen and twenty-eight planes were used for the parallel trials, and four planes were used for the oblique trials. The parallel planes were chosen so as to match those currently used in clinical practice, and the oblique planes were chosen so that when combined with two or three of the parallel planes, they would capture the shape of the structure with as few planes as possible. The order of the ten datasets was randomized, and the order of the parallel and oblique trials was alternated to compensate for any learning effect.

Images of the results from the brainstem case A and of the prostate case B are shown in Figure 5. The contours of each of the five users are displayed in a different color. Colored dots on the oblique planes represent the intersection points of the plane with contours drawn on the other oblique planes.

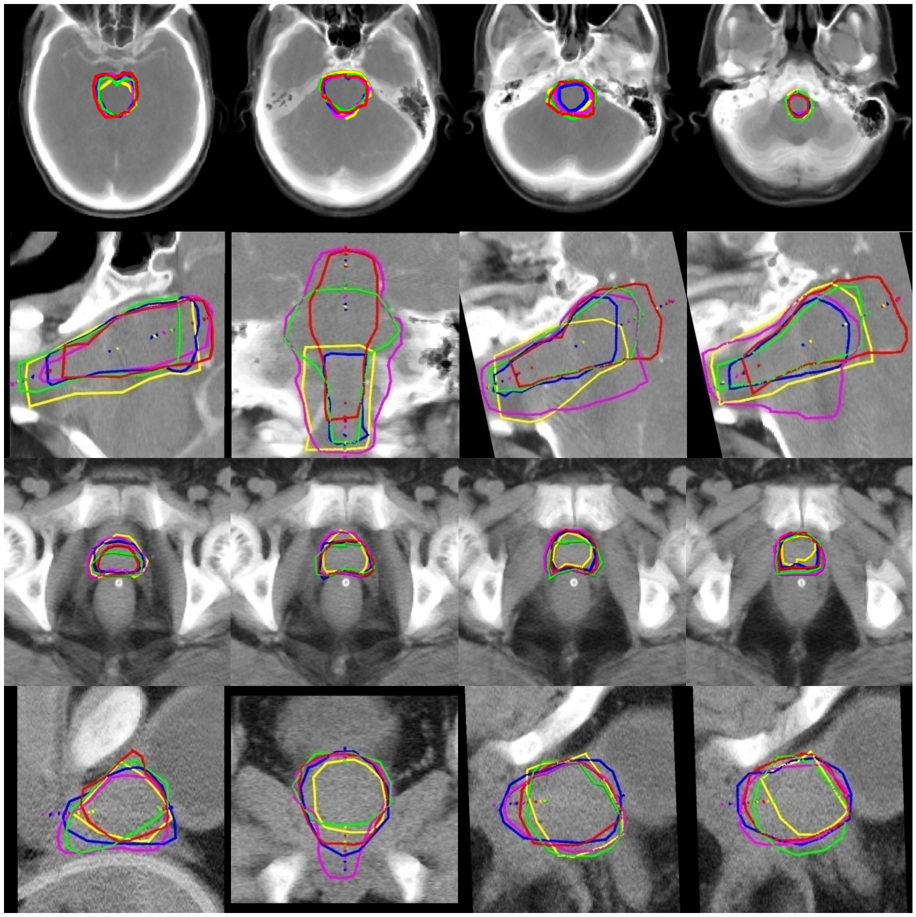


Figure 5: *Inter-observer variability of experts. Each row contains four cross-sections from the following cases: (Top row) Brainstem-A Parallel, (Second row) Brainstem-A Oblique, (Third row) Prostate-B Parallel, (Bottom row) Prostate-B Oblique. The contours of each of the five users are displayed in a different color. Colored dots on an oblique plane represent the intersection points of the other contours with that plane. Note that the variation among users is larger in the oblique cases than in the parallel cases. The users were also largely inconsistent with the other contours that they drew in the oblique cases.*

These images show that the variation among users was much larger in the oblique cases than in the parallel cases.

4.2. Intra-observer Variability of Experts

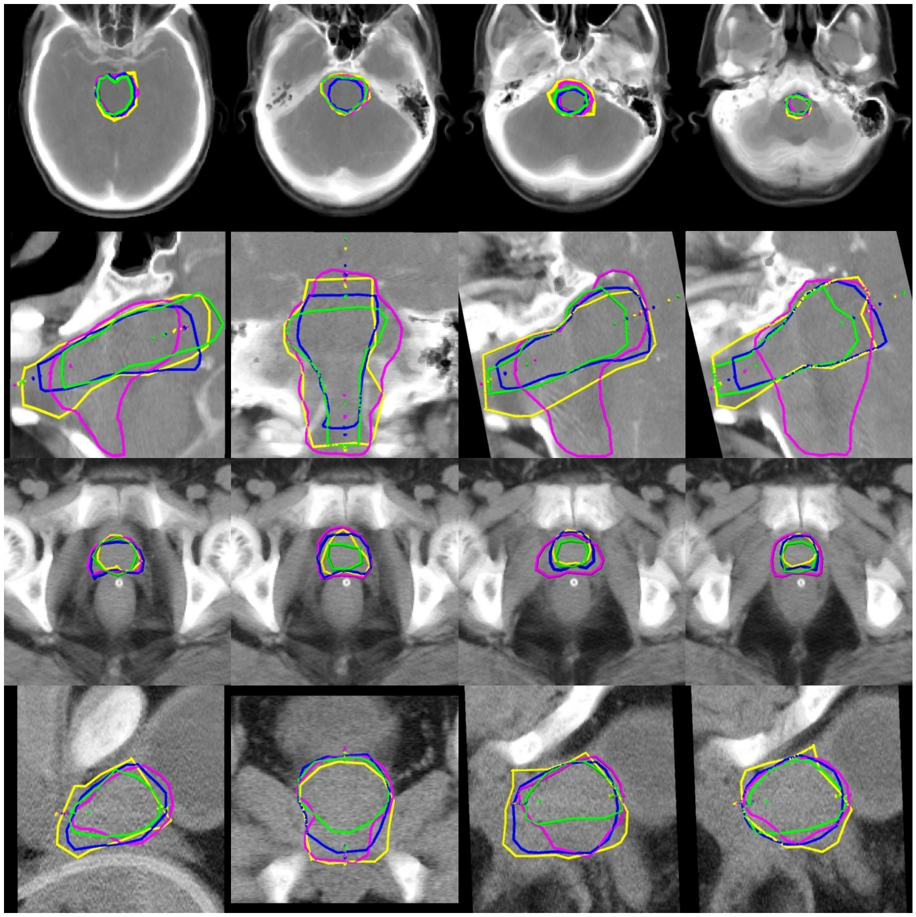
Several weeks later four of the five users were asked to repeat the structure segmentations. The study design was exactly the same as before, except that they were asked to contour four of the ten original datasets (two prostate, two brainstem). Images of the results from the brainstem case A and of the prostate case B are shown in Figure 6.

The results illustrate that intra-observer variability was much larger for oblique contours than for parallel contours. In general, the users did not draw highly similar contours to what they had drawn before on the oblique planes. Also, there was no significant improvement in consistency between the user-drawn parallel or oblique contours from the first study to the second.

4.3. Analysis

We also analyzed the results quantitatively, by computing the mean distance and percentage overlap between each pair of user-drawn contours for each plane in each case. For the parallel cases, we chose a sample of four planes that were evenly spaced through the dataset. For inter-observer variation (see Section 4.1), we compare the users against one another, and for intra-observer variation (see Section 4.2), we compare each users' contours with the contours that they drew in the previous study.

The mean distance was computed as the average minimum distance between point samples on the two contours, and the percentage overlap was computed as the ratio of the



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number of pixels contained in the intersection of the two contours to the number of pixels contained in their union. The mean distance measure captures the average distance from one contour to another, while the overlap measure normalizes for the size of the contour. We then averaged these numbers across all five cases for the prostate and the brainstem.

The results are shown in Figure 4, and corresponding p-values are provided in Table 1. Comparisons between parallel, oblique, and oblique reference image studies were carried out using Friedman's two-way non-parametric analysis of variance followed, if significant at the 0.05 level, by Wilcoxon signed ranks tests. The Bonferroni correction was applied to correct for repeated measures, thus a p-value below 0.017 indicates that the two groups do differ significantly. This analysis further confirms that variation among users was significantly larger in the oblique cases than in the parallel cases.

5. Observations and Hypotheses

Users were much more consistent drawing parallel contours than oblique contours. We propose several hypotheses to explain this negative result. First, the users had considerable experience interpreting imaging data using the parallel planes, as this is the current standard of practice in radiation oncology. Yet, the interpretation of oblique image planes was limited to a brief tutorial and two example cases. Users were given no additional imaging or spatial location information to assist with oblique image planes.

In addition, for the brainstem and prostate the parallel contours were generally smaller and more symmetric than the oblique contours. The image data is noisy, making it very

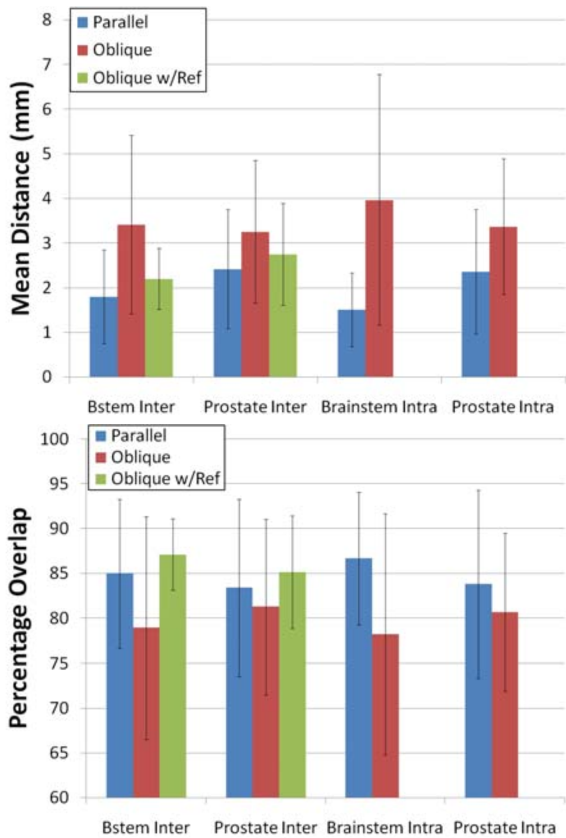

Figure 4: *The average mean distances (top) and average percentage overlap (bottom) between user drawn contours. "Inter" and "Intra" refer to the results from the inter-observer (see Sections 4.1 and 6) and intra-observer (see Section 4.2) studies, respectively. "Oblique w/Ref" refers to the results from novices drawing on oblique planes with reference images (see Section 6). Intra-observer variation was not measured for this case. Note that the average distance between user drawn contours was higher and the percentage overlap lower for the oblique cases than the parallel cases. The average distance between oblique contours drawn by novices using reference images was lower and the percentage overlap higher than for the oblique contours drawn by experts without reference images.*

difficult to delineate the boundary, but if the user is able to delineate part of the boundary in the parallel cases, the rest can often be completed by symmetry. This is not the case for the irregular shaped oblique contours in our examples.

Finally, the Next and Previous buttons provide more information for the parallel cases than the oblique. For the parallel cases this corresponds to paging forward and backward through the image stack. One parallel contour can be used as a template for the next parallel contour in the stack. This is not the case for the oblique contours. The next oblique plane is at a completely different location and orientation from the one before it, and the 3D navigation tools (Section 3) were not enabled, so the user could not rotate the plane or move it along its normal.

The results from these first two studies imply that some form of additional training for drawing contours on oblique image planes is required in order to achieve consistency between users. Our follow-up study investigates one possible training mechanism.

6. Follow-up Study

For this study, we invited five novice users, without any experience marking contours on medical images, to participate. We chose novice users because if our hypothesis is correct that the expert users rely largely on pattern recognition from contours that they have seen before in the parallel cases, then we should see improvements in consistency when training images are provided, even among novice users. As our goal was to improve consistency on the oblique planes, we did not have the novice users contour on the parallel planes.

The datasets and design for this study were exactly the same as those used for the intra-observer study (Section 4.2), except that we only had the users contour on the oblique planes and added one new window to the interface. This new window is highlighted in yellow, with two possible views, in Figure 3. For each oblique plane, the window contained four reference images. Three of these images show example contours drawn on similar cross-sections of the anatomy of three different patients. These contours were made by intersecting the oblique planes with a surface model reconstructed from many physician-reviewed contours drawn on the parallel cross-sections of the dataset. The contours can be toggled on and off, to give the user a sense of what they should be looking for in the image data. The fourth image illustrates which cross-section the user is currently observing, by showing its position as a slicing plane through a surface model of the anatomy.

The results are shown in Figures 7 and 4, with corresponding p-values in Table 1. Given the training images, the novice users were much more consistent marking contours on the oblique planes than the experts. While the mean distances for the brainstem case were still larger than that of the expert-drawn parallel contours, the mean distances for the prostate case and the average percentage overlaps were not significantly different.

We hypothesize that if we were to run this study on the expert users again with the use of reference images, that we would see similar results. However, we have chosen not to do this largely due to signs of user fatigue after the intra-observer study. In future work, we plan to incorporate this and other tools into a composite system and examine the whole process of contouring, surface reconstruction, editing, and review as compared to the parallel case.

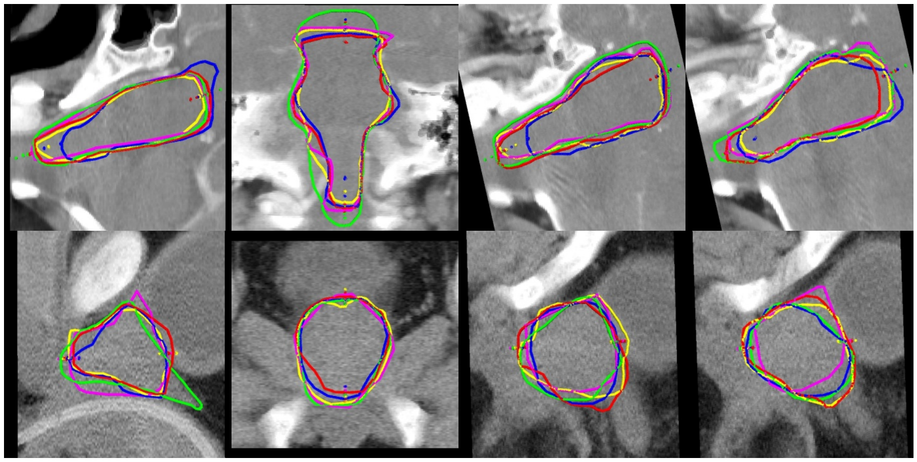

Figure 7: *Inter-observer variability of novices with reference images. Each row contains four cross-sections from the following cases: (Top row) Brainstem-A Oblique, (Bottom row) Prostate-B Oblique. The contours of each of the five users are displayed in a different color. Colored dots represent the intersection points of the other contours with that plane. Note that the variation among users is smaller than in the previous studies (see Figures 5 and 6). The users were also more consistent with the other contours that they drew in the oblique planes.*

7. Conclusion

We have presented a novel sketch-based interface that allows the user to reconstruct surface models from volume data by marking contours on arbitrarily oriented image planes. Through the results of two user studies, we have shown that the inter-observer and intra-observer variability of oblique contouring by physicians is much higher than for parallel contouring. We have presented our hypotheses as to why this disparity exists, and have shown that the consistency can be greatly improved in novice users simply by integrating a collection of reference images into the interface.

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