Spatial Analysis Tools for Virtual Reality-based Surgical Planning

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Abstract

This paper presents a set of Virtual Reality-based interaction techniques for spatial analysis of medical datasets. Computer-aided medical planning tools often require precise and intuitive interaction for the quantitative inspection and analysis of anatomical and pathological structures. We claim that measurement tasks can be carried out more efficiently using Virtual Reality-based interaction tools rather than using common 2D input devices used for medical workstation. Due to the true direct manipulation of three-dimensional virtual objects, measurement tools can be used easily in 3D. An evaluation performed with a group of 20 subjects provides evidence to back up our claims.

CR Categories: H.5.2. [Information Systems]: Information Interfaces and Presentation—Interaction styles

Keywords: 3d measurement, spatial analysis, surgery planning, direct manipulation

1 Introduction and Related Work

In computer-aided medical diagnosis and treatment planning it is not sufficient to just perform qualitative inspection of the data. Quantitative analysis, such as measurements of distances, volumes or angles, is often required. Currently, surgeons often have to build their own mental three-dimensional (3D) model of complex anatomical structures based on the information extracted from two-dimensional (2D) computed-tomography (CT) images, with the aid of 2D-based measurement tools. In contrast to radiologists, who are highly trained in this form of abstraction due to their daily routine, analyzing 2D images is a hard task for surgeons who are naturally more 3D-oriented. The problem is intensified by the increasing scanner resolutions producing hundreds of 2D slices which are hardly manageable even by skilled radiologists. These limitations lead to a motivation towards using 3D visualization in computer-aided medicine, especially for surgical planning tasks.

Several groups already presented prior work for surgical planning environments and suggest specific input devices and VR-based interaction metaphors for their specific problem domain [1, 5, 4, 8, 14, 16, 11]. In their clinical evaluations, surgeons rated the developed tools as useful and see a strong impact of these tools on the clinical workflow in future. In a state-of-the-art report concerning surgical planning environments [15], interaction is rated as the key to a successful planning system.

However, quantitative measurement tools and corresponding interaction elements are not yet well established for 3D visualization in general, and not fully addressed in the above mentioned surgical planning publications. Commercial 3D systems provide only very basic measurement tools. Some research systems concentrate on specific 3D measurements, e.g. intra-cranial [10] or surgery [9, 6]. The most elaborate 3D measurement toolkit was presented by Preim et al. [17, 18]. They introduced a set of 3D widgets including distance lines, rulers, angular measurements and interactive volume approximations. All widgets are manipulated on a regular desktop workstation using the mouse.

While such desktop-based 3D systems sometimes claim to provide more natural "direct manipulation" of 3D structures compared to their 2D precursors, the style of interaction using a mouse is actually indirect when compared to an immersive Virtual Reality (VR) setup. Obviously, strong depth cues are important for correct and fast spatial perception [22, 26]. As pointed out by Mine [13], working within arms reach with a stereoscopic head-mounted display (HMD) provides strong depth cues, allows fine motor control and takes advantage of proprioception. Mason et al. [12] show that an VR setup that provides visual feedback about the moving limb is extremely important for humans to effectively work in 3D. Wang and MacKenzie [25] demonstrate that contextual haptic feedback such as a physical table surface or hand-held plate improves 3D interaction as well.

All these studies lead us to believe that also 3D measurements which build an integrated part of a surgical planning environment can be better carried out in a VR environment rather than on a 2D desktop-based application. In this paper, we report on the 3D measurement toolkit developed for the Virtual Liver Surgery Planning (VLSP) system [2]. We start with an overview of the overall surgical planning system, then we describe the design and interaction aspects of the new 3D measurement tools, and report on an evaluation with 20 subjects that provides encouraging evidence of the usefulness of our approach. For the developed tools, 3D interaction can fully be exploit in order to allow an easy-to-use measurement toolbox. They can either be used in a semi-immersive or an immersive environment. However, the developed props are only useful for semi-immersive setups.

2 Virtual Liver Surgery Planning System

The Virtual Liver Surgery Planning system aims at assisting surgeons and radiologists in making surgical decisions regarding the surgical treatment of liver cancer, in particular different kinds of liver tumor resections. This procedure requires careful three-dimensional planning to specify the tissue to be removed and the access path to the tumor, in order to ensure complete removal of the tumor while minimizing the removal of healthy tissue and bleeding. The liver is not homogeneous but structured into segments with independent blood-feeding vessels. In current clinical routine using 2D slices, important quantitative indices such as the location, volume and spatial extension of the tumor or the distance between a major vessel branch and the tumor are often only estimated. Wrong surgical decisions result from such rough estimations.

The VLSP system uses a VR setup based on the *Studierstube* [1] platform [21]. It provides a real-time three-dimensional visualization of the patient's liver, together with a set of tools for interactive analysis. The visualization is either presented using a large screen stereoscopic projection system with shutterglasses or a head-tracked stereoscopic head-mounted display. Two-handed interaction is provided through a tracked pen and panel interface [23].

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[1] http://www.studierstube.org

The visualization uses a deformable surface-based model of liver, vessel system, and tumors. The models are computed through (semi-)automated segmentation from CT scans, and can be refined with interactive segmentation refinement tools used by a radiologists [3]. The resulting segmented models are then inspected by the surgeon to plan the intervention. Among other surgical planning tools like interactive liver segment approximation or liver partitioning, a set of measurement tools is required for the quantitative assessment of important indices. For instance, the volume of the tumor or removed tissue, the distance between a main vessel branch and the tumor, or the angle between two main vessel branches.

For this reason we identified together with our clinical partners the following three-dimensional measurement tools required for a surgical planning environment:

- **Distance measurements**: free-handed measurements are important to verify manually if a required safety distance around tumors is guaranteed in all places, or to measure the minimal distance between two tumors. In addition, the measurement of distances between tumors and major vessel branches are often required.
- **Volume measurements**: both absolute and relative volume measurements are extremely important to assess the size of the tumor, and the remaining liver tissue after the resection. A measurement jug is necessary for calculating accumulated volume of different objects.
- **Angular measurements**: angular measurements are mainly useful for determining properties of the geometric configuration of extended objects, such as important branches of the vascular structures.

3 Interactive Measurement Tools

3.1 Distance Measurements

Three distance measurement tools were developed, which fit the requirements of quantitative analysis during surgical planning procedures.

3.1.1 Point-To-Point Measurement

The simplest option for measuring distances allows a user to drag a three-dimensional "rubberbanding" line by pressing and holding the button on the pen. The line is shown as a thin tube with conical arrowheads (see Figure 4). Real-time display of the current length allows interactive probing of distances from a common start point. After the initial placement of the line, the measurement can be refined by grabbing one of the line's endpoints and making adjustments. In contrast to desktop 3D interaction, users can zoom in instantaneously by moving closer to the virtual objects. However, for more precise placement (for example, to compensate unsteadiness of the hand), the virtual scene needs to be enlarged by modifying the zoom parameter.

3.1.2 Snap-to-Object Measurement

In some cases, the user is more interested in precise inter-structure distances. Therefore, the distance measurement tools include an automatic snapping to the nearest object surface after pressing the action button. Real-time behavior of this tool is achieved by using a kd-tree auxiliary structure. This mode can also be used as a constrained measurement for minimal distances. The nearest point on the next surface found is marked by a transparent sphere (see Figure 4(a)).

3.1.3 Interactive Ruler

A ruler is a very common facility for measuring distances in real life. Therefore, a tracked physical ruler of about 40cm length (see Figure 1 for an overlay image) is introduced as an interaction prop for fast determination of distances. It can be operated with one or two hands, and affords virtual scales (overlaid on the ruler, or digital numbers floating over the ruler in space). An additional important feature of the ruler is the capability of measuring minimal distances semi-automatically. For that aim, the ruler controls a straight line used to intersect objects. The distance between the nearest intersections on both sides of the ruler is interactively reported. A collision between the ray specified by the ruler's position/orientation and the bounding boxes of each object is performed. For all intersected objects, a fast line-triangle intersection is calculated.

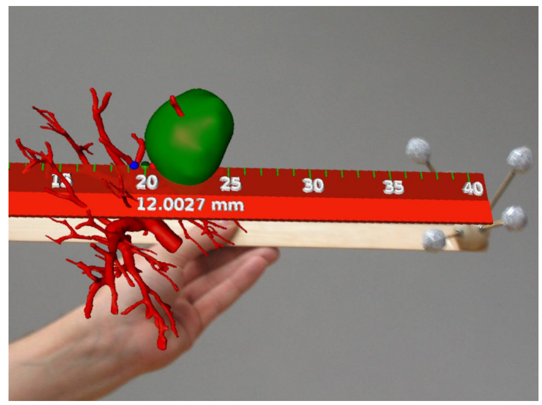


Figure 1: An additional props – the interactive ruler – can be used for measuring distances in a semi-automated way. The number displayed at the center of the ruler indicates the distances between two surface intersection points.

3.2 Volume Measurements

Volume measurement is extremely important to assess the size of the tumor, and the remaining liver tissue.

3.2.1 Direct Volume Measurement

In the direct volume measurement mode, the pen must be moved inside the desired volume, which is highlighted for feedback. By pressing the pen's button, a geometrical volume calculation algorithm, described below, is applied on-the-fly. Several measurement algorithms exist in literature which allow volume calculation of surface-based objects in real-time. For our purpose, we used the algorithm presented in by Reitinger et al. [19]. The numeric information that has been obtained is temporarily attached to the pen's tip and can be positioned in space. Color coding allows to identify which measured value belongs to which volume (see Figure 5).

3.2.2 Measurement Jug

The direct volume measurement method allows the calculation of individual objects. However, for treatment planning, a volume calculator is required to measure the aggregated volume of multiple objects (e.g., the volume of two or more resected tumors, or the volume of multiple liver segments). For this purpose, we added another tracked prop, the measurement jug, to our toolbox. Virtual objects can be deposited in the jug using simple drag and drop with the pen. Each object is represented by a color coded virtual slice in the jug, with the height of the slice corresponding to the object's volume. The overall volume is displayed numerically on top of the jug (see Figure 2 and 6). To improve the overview in case of a cluttered display with many different volume objects, the ones deposited in the jug can be rendered invisible until the jug is emptied by a turnover gesture.

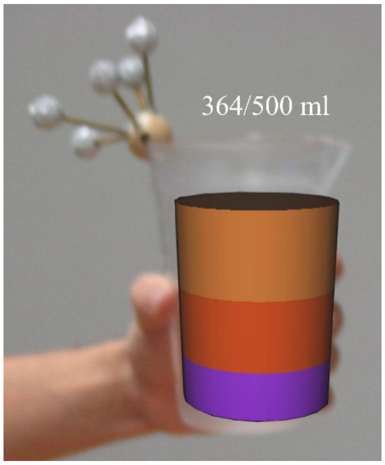


Figure 2: The measurement jug, shown as an overlay image, can be used as a volume calculator where volumes of individual objects are summed up. The overall measured volume is displayed numerically on top of the jug.

3.3 Angular Measurements

Angular measurements can be necessary for analyzing the vascular structure. Angles between branches are often important for planning access to the tumor during intervention. The geometry of the angular measurement tool is similar to the distance measurement tool. Two cylinder-shaped lines span an angle in 3D, the lines are delimited by two conic endpoints, while the apex corner is visualized by a sphere (see Figure 3). By placing the pen and pressing the button, the user specifies the apex and the two endpoints. Both cones and the sphere can then be further adjusted by the user.

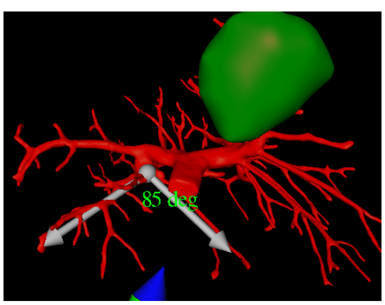


Figure 3: The angular measurement tool can be used for analyzing the geometry of different branches of the vessel tree.

3.4 Automated Measurements

In addition to manual measurements, which give full control to the user, automated measurement of distances and volumes are provided for cases when overall assessment of objects is of interest.

3.4.1 Minimal Distances

Minimal distance calculation can be applied for two disjoint objects (for instance two tumors). For treatment planning it is sufficiently accurate to calculate the minimal distance on the basis of surface vertices (currently through a brute force approach, which is sufficient for our objects' resolutions).The minimal distance measurement is triggered by selecting two disjoint objects with the pencil. After the calculation, a distance line is drawn indicating the length and position of the distance. For measuring the minimal distance between non-disjoint objects (e.g. one major branch of a vessel structure and a tumor, if other branches of the vessel structure are intersecting the tumor), automated algorithms cannot be applied without manually altering the object topology. However, the interactive ruler or the snap-to-object mode can be used for this task.

3.4.2 Object's Extensions

Another automated calculation is the maximal object extension which is necessary for analyzing the spatial extensions of the liver or tumors. The user simply selects the desired object with the pen, and the maximal extension is computed. The calculation is done through principal component analysis (as proposed by [18]), and the result is drawn inside the transparently rendered target object as three orthogonal cylindric lines indicating the principal components.

4 Evaluation and Results

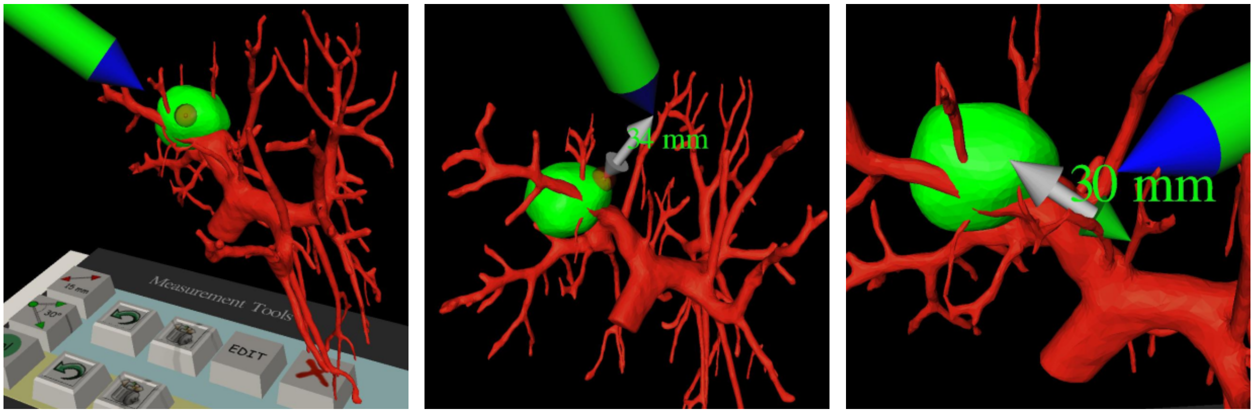
To evaluate our main hypothesis that spatial measurements can be more efficiently carried out in VR compared to a traditional medical planning system, we conducted an evaluation comparing two conditions: a standard medical application called *OsiriX* [28], and the presented measurement toolkit of the *VLSP system*.

4.1 Evaluation Setup

The first condition – OsiriX – is a desktop-based system which is a frequently used platform for medical diagnosis mainly controlled by a standard mouse. Several visualization possibilities are available such as volume rendering, surface rendering by thresholding, and a 2D multi-planar reconstruction (MPR) technique which allows the extraction of a slice in any position and orientation of the 3D volume by moving and rotating line-modifiers (see Figure 7). Once the correct slice is found, measurements (i.e. distance measurement) can be performed.

For the second condition – the VLSP system – we used a semi-immersive large-screen stereoscopic back-projection system with a size of 3 m $\times$ 2.40 m and a resolution of 1280×1024. The subject was wearing tracked shutterglasses, and perceives the scene with 60 frames per second/eye. The distance to the projection wall was about 2 meters. The influence of different output devices (e.g. HMD, shutterglasses) on accuracy was not focus of this evaluation since a study has already been carried out by Rolland et al. [20]. For tracking, we utilized an optical tracking system from Advanced Realtime Tracking (A.R.T.) [27].

The input devices consisted of a tracked pencil and a tracked semi-transparent personal interaction panel (PIP) [23]. The pen was used for direct interaction, whereas the panel was mainly used for system control tasks and menus. Multiple buttons on the pen allowed a configuration where the first button is for interaction tasks, the second is for moving and the third one is for scaling the scene. For the evaluation, both measurement props presented in the previous section were not used.

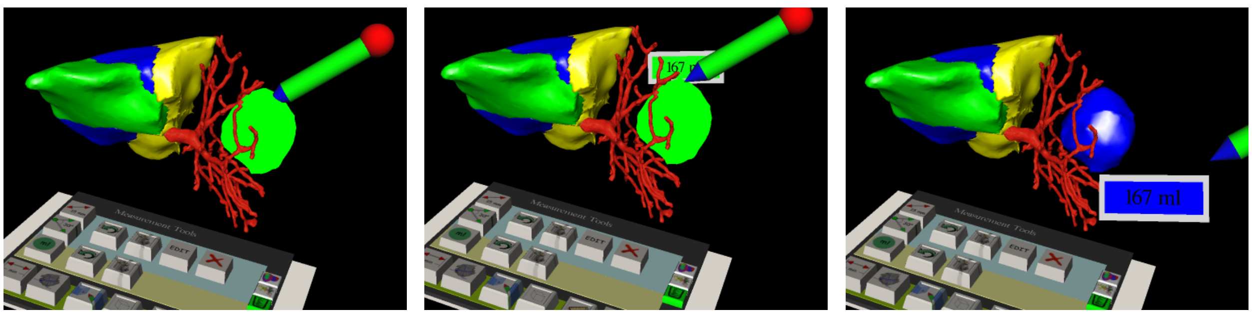


(a) Using the snap-to-object mode marks the nearest point on the next registered object with a sphere.

(b) By pressing the button on the pencil, the starting point of the distance line is snapped to this position.

(c) Line modifiers can be edited if the pencil's position is next to a cone (highlighted green).

Figure 4: Different modes for dragging a distance line in 3D.

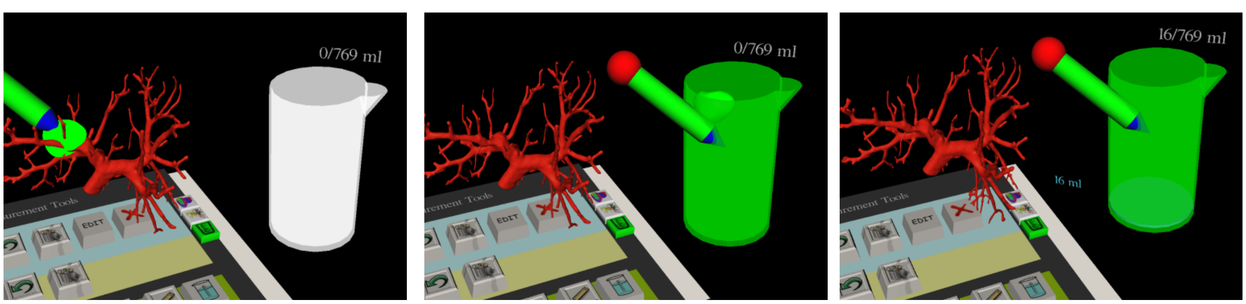


(a) The pencil is used for selecting a target object (highlighted in green).

(b) By pressing the button, the volume is calculated on-the-fly and attached to the pen's tip.

(c) The quantity can be positioned in space.

Figure 5: The pencil is used for triggering a volume calculation for a selected object.



(a) Initially, the object is selected by the pencil (highlighted in green).

(b) The selected object is attached to the pencil and can be dragged in the measurement jug.

(c) By releasing the button, the object's volume is indicated by a slice in the measurement jug.

Figure 6: The measurement jug can be used for calculating the sum of different objects. By drag and drop, individual objects can be deposited in the jug, and the overall volume is displayed numerically on top of the jug.

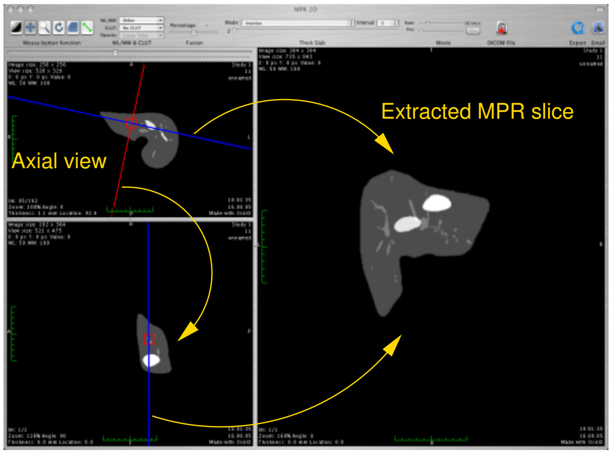


Figure 7: This screenshot shows a phantom medical dataset viewed in OsiriX using the 2D MPR technique. The upper left view displays an axial view from the top, the lower left view shows the interpolation of the upper red line, and the most right view shows the extracted slice of the blue lines specified in the previous views.

Data Preparation We prepared three different phantom medical liver datasets, each containing a liver, a vessel tree (where two branches are marked for angular estimation), and two tumors (see Figure 8). All three datasets show up a variation in tumor sizes, distance lengths between tumors, and angles between two target branches which were highlighted. Since all datasets were generated by a prior segmentation, the VLSP system rendered all objects using a surface representation. In case of OsiriX, a 3D voxel-based dataset was generated where a unique label was assigned to each individual object. This dataset could either be browsed slice-by-slice in z-direction or investigated using the 2D MPR technique.

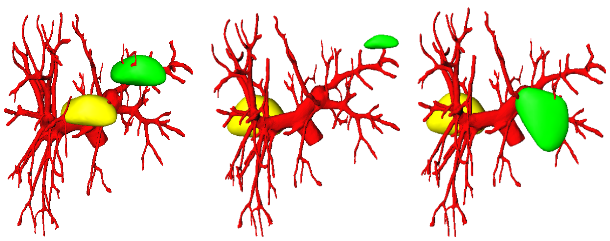


Figure 8: Prepared phantom medical datasets which were used for the evaluation in the VLSP system.

Subjects and Procedure 20 subjects participated in the evaluation, 12 male and 8 female, ranging between 18 and 32 years old, with an average age of 26. Each subject had to rate the experience for 2D interaction, VR interaction, medical background, the VLSP system, and OsiriX with a score between 1 and 5 (1 no and 5 much experience). A summary of the ratings is shown in the Table 1.

Each subject had to perform five different tasks on each condition (angular estimation, minimal distance estimation as well as measurement, relative volume estimation, and volume measurement). The following list describes all tasks which were carried out in detail:

- **Volume estimation**: subjects were asked to estimate the relative volume of the first tumor compared to the second one. For this task, they only used navigation capabilities of the visualization system available on each condition, without the aid of a built-in measurement tool.

- **Volume measurement**: subjects were asked to use the built-in volume measurement tool (as good as possible) on each condition for recording the task completion time.

- **Distance estimation**: the user was asked to estimate the minimal distance between two tumors only using navigation (including MPR in 2D). A sphere in the dataset (20 mm in diameter) was used as reference distance.

- **Distance measurement**: the user was asked to use the built-in distance measurement tool for measuring the minimal distance between two tumors. In VR, the minimal distance was calculated three times. At first free-handed, second using the snap-to-object facility, and finally using the automated minimal distance calculation.

- **Angular estimation**: the subject was asked to estimate the enclosing angle of two highlighted branches of the vessel tree without using built-in tools.

Experience in	Average score
2D interaction	4.35
VR interaction	2.75
Medical background	2.15
VSLP system	1.85
OsiriX	1.05

Table 1: Ratings about the subjects' experience in certain fields. A score between 1 and 5 (1 no and 5 much experience) was possible.

Since OsiriX does not support angular measurements in the MPR mode, no comparison could be made. In addition, OsiriX uses a threshold based volume calculation algorithm, where accuracy of the volume quantity can differ for different user-specific thresholds. However, subjects were asked to measure the volume as precise as possible, in order to measure the task completion time. Since a validation of the used volume calculation algorithms was not scope of this paper, only task completion time was recorded for the evaluation.

For all other interaction tasks, we recorded the achieved accuracy (relative error to ground truth data) and task completion time. In addition, we asked for measuring the minimal distances in the VR environment first only free-handed, then by using the snap-to-object functionality and finally using the automated minimal distance calculation. Since the accuracy of the automated distance calculation depends on the objects resolution, we were only interested in the average completion time for this task.

Three different datasets were prepared for evaluation. One was used for training on each target application, while the other two were used for evaluation (one for the first condition, one for the second condition). All datasets were randomly distributed over all subjects, and within-subject task order was also randomized. A short training of 10 minutes per condition gave the possibility for introducing all required measurement tools.

4.2 Quantitative Results

The means and standard deviations of all tasks and conditions are summarized in Table 2 including an analysis of variance (ANOVA) comparing both conditions. Bold values indicate better performance for a given task. The first column compares the task completion time and the second one the accuracy of the measurements or estimations (the relative estimation or measurement error).

The results indicate a clear benefit for the VR system concerning the task completion time. For all tasks, an ANOVA revealed significant better results for VR interaction concerning time efficiency assuming a p-value of $p < 0.05$ for all tests. Details can be obtained in Table 2, where bold ANOVA values indicate a significant benefit. The corresponding box plots comparing completion times for various tasks are shown in Figure 10.

Concerning the accuracy, the VR measurement tools also perform slightly better for most of the tasks (comparing means and standard deviations of 2D and VR). However, no significant results could be achieved. This can mainly be explained by the fact, that exact measurements are also possible in 2D, if the correct MPR slice is found.

For distance measurements, we compared free-handed and constrained (snap-to-object) interaction. Concerning task completion time, the snap-to-object mode performs significantly best. However, more precise results could not be achieved by using this constrained measurement tool. We also recorded the average interaction time for using the built-in minimal distance calculation in VR, and obtained a mean task completion time of 7 seconds.

4.3 Qualitative Results

In addition, questionnaires were filled out by subjects, stating their personal preference among 2D and VR for measurement tasks. Figure 9 shows a plot where the height of a bar indicates the accumulated score of all subjects for a certain condition. For each individual task, a clear preference for the VR system is indicated. One noteworthy observation is that distance measurements in 2D are preferred by 6 out of 20 subjects. These subjects stated, that dragging a 2D line on a MPR slice can be performed easier by using the mouse. We conclude that a possible improvement of the VR interaction is to let the user choose between direct free-handed 3D measurement and a technique that requires the user to specify a cutting plane in 3D first (similar to [7]), then perform precise measurements within that plane.

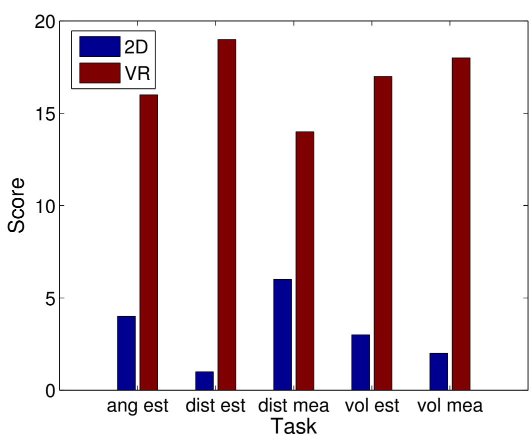


Figure 9: Personal preference among 2D and VR for measurement/estimation tasks. The bars indicate the accumulated scoring for an individual task.

5 Discussion

This paper presented a set of interactive VR-based measurement tools for surgical planning applications. The tools are designed for computer-aided diagnosis and treatment of liver tumors, but not limited to this domain. The main benefit of the new approach compared to a conventional 2D medical workstation like OsiriX is the true direct interaction possibility using 6 DOF input devices, and enhanced visual feedback through head-tracked stereoscopic visualization.

An evaluation indicated that VR-based measurement tools have a significant benefit compared to 2D desktop-based systems in terms of task completion time. Every task could be carried out faster in VR than in the 2D environment. Even in terms of accuracy, slightly better results in most of the tasks were achieved. However, achievable accuracy in VR is limited by the used tracking system including its precision and calibration. We used an optical tracking system, which was rated as one of the best in [24]. However, according to physicians, the achieved precision by our tracking system is acceptable for the developed measurement tasks.

We have also carried out a similar user study with a small group of physicians in order to get feedback of potential users. The results were similar, although accuracy errors concerning volume estimations in 2D were much higher. This can be explained by the fact that physicians, especially surgeons, who are not trained to the radiological workstations in their daily routine, did not use the MPR functionality for estimating volumes. This let us believe, that available functionality of traditional radiological workstations is not fully exploited, which can lead to inaccurate results.

Our discussions with surgeons also confirm that in daily clinical routine time plays an important role, and better tools may allow a surgeon to perform more detailed planning in the available time, leading to a potentially better treatment. In addition, the qualitative results also reveal a clear preference for the VR measurement tools. Especially the interaction with the tracked pen for measurement tasks gained much positive attention. Also, some of them stated that the learning curve for VR interaction is much better than for desktop-based mouse interaction. The measurement jug seems to be very useful for calculating a sum of different volumes. For instance, the sum of volumes of certain liver segments is often required for treatment planning. According the type of output device, a clear preference was towards using projection-based system instead of head-mounted display. Shutterglasses provide a more comfortable feeling and can be used for a longer period of time.

The main limitation of this system if being used in clinical routine is hardware cost. Since a VR setup must be installed, components such as a high quality tracking system or a rendering workstation must be afforded. However, the return of investment may be given by saving a lot of time spend on measurement or on the whole planning process in general.

6 Conclusion

By the development of efficient and intuitive user interaction techniques like presented in this paper, we believe, that 3D spatial analysis tools contributed to increase the acceptance of the overall surgical planning system. However, a full scale evaluation within the clinical workflow will be necessary to assess the overall impact in clinical routine.

For future work, a further evaluation comparing 3D desktop-based measurement tools such as proposed in [18] with the presented VR tools would be interesting. Since indirect 3D manipulators are necessary for a desktop-based system, the comparison to direct manipulation with 6 DOF is valuable.

	task completion time (sec)			accuracy (rel. error in %)		
	2D	VR	ANOVA	2D	VR	ANOVA
Volume estimation	83.15 ± 48.74	$\mathbf{27.70 \pm 18.34}$	$\mathbf{F = 22.67}$	37.29 ± 32.17	$\mathbf{31.96 \pm 27.14}$	$F = 0.32$
Volume measurement	34.58 ± 10.43	$\mathbf{9.80 \pm 9.11}$	$\mathbf{F = 127.97}$	n.a.	n.a.	n.a.
Distance estimation	84.84 ± 50.46	$\mathbf{16.95 \pm 10.56}$	$\mathbf{F = 36.48}$	$\mathbf{37.90 \pm 43.26}$	42.10 ± 25.13	$F = 0.15$
Distance measurement	45.65 ± 31.37	$\mathbf{43.10 \pm 24.92}$		9.95 ± 8.54	$\mathbf{8.51 \pm 6.42}$	$F = 0.15$
Distance measurement (snap-to-object)	n.a.	$\mathbf{22.80 \pm 18.26}$	$\mathbf{F = 8.63}$	n.a.	8.78 ± 10.63	–
Angular estimation	77.65 ± 55.87	$\mathbf{18.45 \pm 10.35}$	$\mathbf{F = 21.71}$	27.39 ± 26.80	$\mathbf{18.88 \pm 18.08}$	$F = 1.39$

Table 2: The overall statistical results of the evaluation shown as means and standard deviations of the estimation/measurement errors and task completion time. Bold values indicate better performance. Except distance estimation, all tasks perform better in the VR setup.

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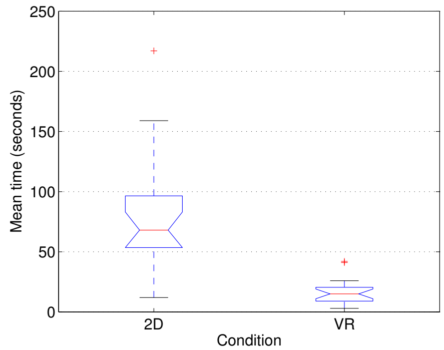
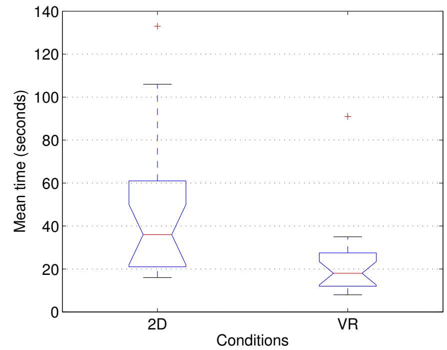
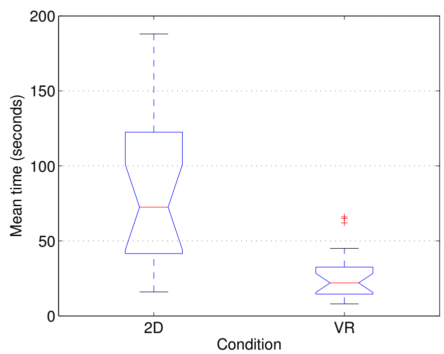


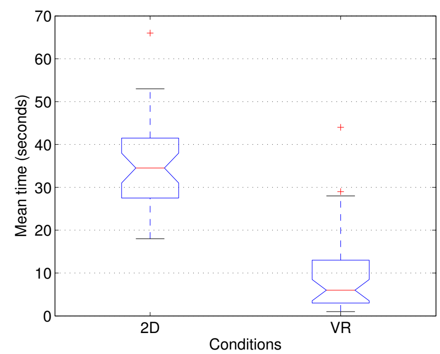
(a) Distance estimation.



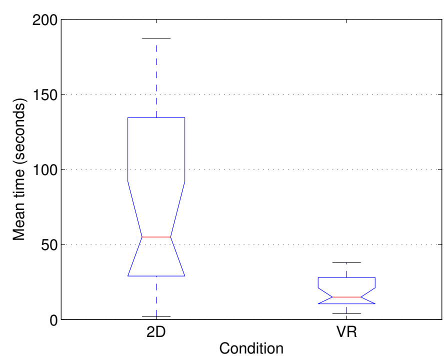
(b) Distance measurement.



(c) Volume estimation.



(d) Volume measurement.



(e) Angular estimation.

Figure 10: These box plots compare the task completion time for various tasks. The left box indicates the 2D condition, and the right box the VR condition.