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ORIGINAL ARTICLE

Interactive navigation of segmented MR angiograms using simultaneous curved planar and volume visualizations

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Abstract

Purpose Interactive visualization is required to inspect and monitor the automatic segmentation of vessels derived from contrast-enhanced magnetic resonance angiography (CE-MRA). A dual-view visualization scheme consisting of curved planar reformation (CPR) and direct volume rendering (DVR) was developed for this purpose and tested.

Methods A dual view visualization scheme was developed using the vessel pathline for both camera position and rotation in 3D, greatly reducing the degrees of freedom (DOF) required for navigation. Pathline-based navigation facilitates coupling of the CPR and DVR views, as local position and orientation can be matched precisely. The new technique was compared to traditional techniques in a user study. Layperson users were required to perform a visual search task that involves checking for (minor) errors in segmentations of MRA data from a software phantom. The task requires the user to examine both views.

Results Pathline-based navigation and coupling of CPR and DVR provide user speed performance improvements in a vessel inspection task. Interactive MRA visualization with this method, where rotational degrees of freedom were reduced, had no negative effect.

Conclusions The DOF reduction achieved by the new navigation technique is beneficial to user performance. The technique is promising and merits comprehensive evaluation in a realistic clinical setting.

Keywords Curved planar reformation · Direct volume rendering · Angiography · Segmentation · CE-MRI · User study

Introduction

Aneurysms and stenoses of the carotid artery and abdominal aorta cover an important class of the most common fatal vascular diseases [3,23]. 3D imaging techniques are considered particularly appropriate for diagnosis, such as computed tomography angiography (CTA) for abdominal aortic aneurysm (AAA) [23] or magnetic resonance angiography (MRA) for atherosclerosis [2,3]. We will concentrate on MRA because we have the most experience with it, but our study is likely to be applicable to CTA as well. MRA acquisition has been widely accepted for carotid endarterectomy screening and diagnostic procedure. It gives as accurate results as the more expensive (and invasive) conventional angiography and CT angiography. Compared to CT, MR is safer for patients [16,24].

Segmentation of the vessel lumen is often a central step in such diagnosis and can be done effectively using an MRA image [10]. After segmentation, the segmented lumen can be used for (possibly quantitative) diagnosis [7]. Segmentation can be done manually or semi-automatically. In both cases, the relationship between segmentation and volume data has to be visualized in order to provide a correct end result. We concentrate on the clinical task of creating or correcting these segmentations.

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With the increase in resolution of medical volume data, medical practice has moved from viewing individual cross-sections to more advanced representations such as volume visualization and data reformation. Several visualizations have been proven especially useful for MRA, in particular C(M)PR (curved (multi)planar reformation) [9], DVR (direct volume rendering) [12], and MIP (maximum intensity projection) [15]. With the advent of computer-based displays and real-time generation of visualizations, it has also become possible to *navigate* through the data, that is, manipulating visualization parameters and sequentially examining different parts of the data. With navigation also comes the concept of *coupling*, linking navigation of one view to another in some meaningful way. With appropriate coupling, the clinician can use multiple simultaneous views more efficiently. Coupling usually involves coupling common view parameters (position, orientation) across the different views. A good example of coupling (of general human body images) is described in the Visible Human Project [13].

With the introduction of interactive visualization, the complexity of system design choices further increases. We argue that new studies are required to evaluate the many different alternatives that emerge. User studies on interactive visualization are relatively rare and are even considered an under-represented element in visualization research in general [8]. Therefore, we present a comparative user study that follows clinical practice more closely than other studies. We summarize some of the literature first.

3D navigation in general is known as a hard problem [18]. In 3D navigation, there are a total of 6 degrees of freedom (DOF): three coordinates for position and three angles for rotation. Particular issues are how to control all 6 DOF intuitively and avoid getting lost or disoriented. While the mouse is still the most commonly used for 3D navigation, many special input devices have been devised for 6 DOF input [27]. However, most of these have drawbacks, such as accuracy problems or other practical problems such as unwieldiness, fatigue, requiring significant training [22], or requiring the user to stand up. Additionally, most of these devices are still expensive.

Even with such devices, it usually proves practical to reduce the DOF to a more manageable level. The best choice for DOF reduction depends on the task. Typical DOF reductions are restricting the camera to a plane [6] or to a curved line [18]. Usually rotation is not constrained, or constrained so that the camera stays upright in case there is a clear "up" and "down". The availability of rotation is important, as it is generally considered a strong visual cue [26].

As regards coupling, one important principle for coupling multiple views is the principle of *complementarity* [25]: each view shows information that cannot be made visible on other views, so that they complement each other. We propose that using multiple complementary views will improve coverage of the information needs of the clinician. We will study the combination of CPR and DVR. CPR is found to be a very useful visualization, showing a lot of relevant detail, but is known to be weak in showing the 3D topology and curvature of a vessel [1,9]. Therefore, a 3D visualization like DVR or MIP will provide relevant complementary information. We chose DVR because it shows occlusion cues (visual cues indicating when one vessel is in front of another).

Creating a CPR requires a pathline through the vessel's center to be specified, which forms the central axis of the curved plane. This is typically done manually, but can also be done automatically. In fact, determining a pathline is often a first step of various vessel segmentation algorithms [5]. We assume that the pathline is determined automatically as part of the segmentation. Accuracy of current algorithms is high enough so that the pathline is accurate in most areas and is at least close to the actual vessel in areas where it is inaccurate. This makes an automatically determined pathline a viable option for CPR and navigation. Errors in the pathline can be examined in the same way as errors in the segmentation.

We use the straightened variant of CPR, which is topologically distorted in such a way that the CPR's central axis becomes a straight line. Its advantage over non-straightened CPR is that there are no curvatures in the visualization that depend on the choice of orientation of the CPR's vector of interest. The DVR can be used to examine the vessel's curvatures.

When we have two visualizations, navigation can be further simplified by means of a coupling scheme. So, we argue that the choice of coupling of CPR and DVR may significantly influence the clinician's performance. CPR and DVR are topologically different, so coupling is conceptually problematic. Navigation in CPR has 2 degrees of freedom (DOF): movement along the vessel axis and rotation around the axis. The same navigation is meaningful in DVR, *if* we assume one particular point as the point of focus (see also the work of for example Plumlee and Ware [14] who call this the *frame of reference (FoR)*). Both views are then centered on the same point, and rotation angle can also be coupled. Local orientation in CPR is defined by the pathline vector at a particular point, with the remaining degree of freedom (being the plane's local angle in the radial direction) determined by the vector of interest. The same rotation angle can be reproduced in DVR, resulting in a "side view", which is orientation equivalent to the CPR at that particular point. We propose that this highly constrained navigation with tight coupling of position and orientation may be a significant improvement over less-constrained navigation and coupling.

In our user study, we examine how users use a dual CPR–DVR view when performing a visual search task involving checking the correctness of a given segmentation. Our main experimental variable is the manner in which the CPR and DVR views are navigated and coupled. We designed a visual search task, based on our experience with real-life data, that requires the user to navigate both views.

Materials and methods

Task

The user task consists of finding errors in automatic vessel segmentations based on MRA. This task involves the complete inspection of one particular segmented vessel in each scan, in analogy with typical diagnosis tasks. Other vessels are also present, but these are added as distractors. Significant navigation is required to examine all relevant data.

When the user finds a segmentation error, s/he has to select the erroneous region by selecting all pathline points that are part of the region. The user has to select the region as precisely as possible; selecting too few or too many points increases the user's error rate. Error rate is effectively a continuous value; even an "accurate" selection usually still has an error rate above zero. The precision required for this task implies that the user has to use both views to perform it optimally. The CPR view shows the general location of errors the most easily, while the DVR shows some details more accurately. Especially for errors where the segmentation veers away from the vessel lumen (sometimes to a nearby vessel), the DVR more clearly shows the shape, direction, and extent of the deviation, and the proximity of other vessels.

We compare user performance (time taken and error rate) for the following four navigation methods. The methods vary in terms of navigation (positioning and orientation of the "camera") and coupling (whether the camera positions of the two views are coupled or can be moved independently). Navigation is either navigation along the pathline (the camera moves back and forth along the pathline, so that the pathline remains centered) or free navigation (the camera may move and rotate in any direction).

- AXIS. All navigation is along the pathline. Rotation is possible around the vessel axis only (1 DOF). CPR and DVR are coupled. This is the constrained navigation method that we propose, which has a total of 2 DOF.
- COUP. All navigation is along the pathline. In DVR, there is free (3 DOF) rotation. CPR and DVR are coupled. This is the same as AXIS, except the user can freely specify relative rotation. Total DOF is 5.
- UNCOUP. All navigation is along the pathline. In DVR, there is free (3 DOF) rotation. CPR and DVR are uncoupled (that is, they can be navigated independently). Total DOF is 6.
- FREE. In DVR, there is free (6 DOF) navigation. In CPR, there is navigation along the pathline. CPR and DVR are uncoupled. Total DOF is 8.

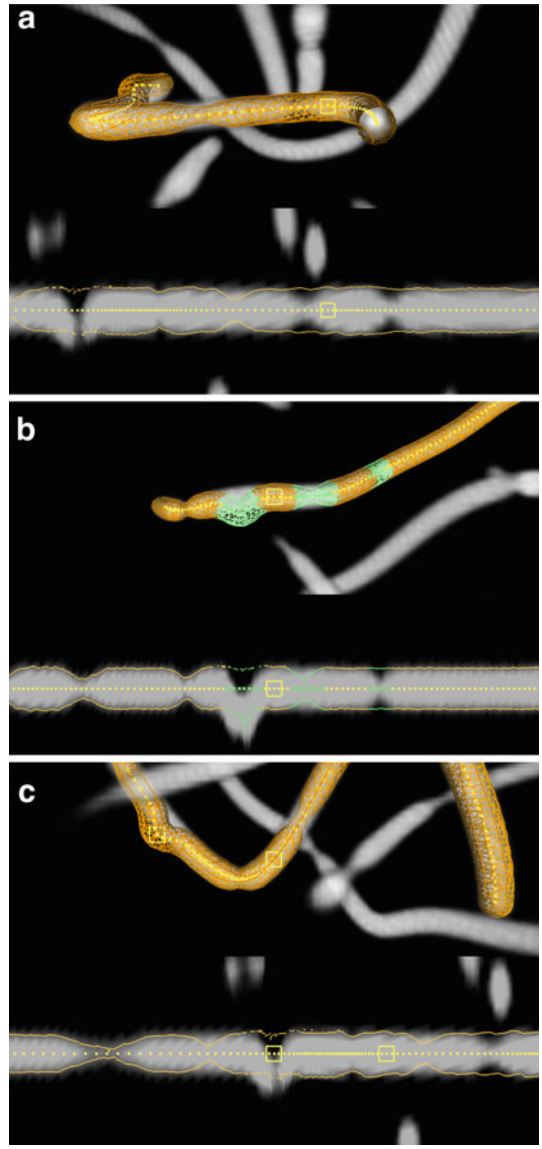

Fig. 1 Illustration of the dual CPR–DVR view as presented to the user. In each image, the *top* half represents the DVR view, the *bottom* half the CPR. *Top* coupled view (COUP). *Middle* coupled with axis rotation only (AXIS), with error regions selected (*bright green* areas). Note the orientation of DVR and CPR is exactly the same around the focus point. *Bottom* uncoupled view (UNCOUP). Note the two focus points. A series of *yellow points* connected through a *yellow line* indicates the pathline, and the *brown* mesh indicates the segmentation

See Fig. 1 for an illustration of the dual views presented to the users.

We hypothesize that pathline-based navigation is an effective method, which means that we expect FREE to perform worse than the other three conditions. As regards UNCOUP versus COUP, since we ask users to do a task that is best performed with both views, we expect them to couple the views manually when not coupled automatically. Hence, we expect UNCOUP to perform worse than COUP. However, there are

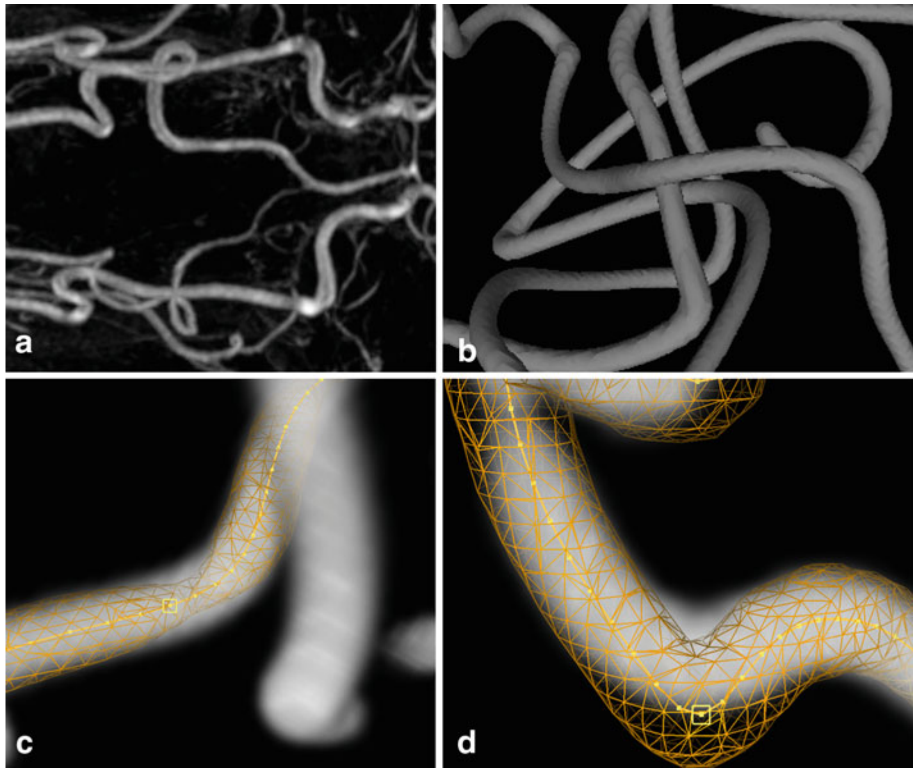

Fig. 2 Illustration of the software phantoms. *Top*, from *left* to *right*: real-life carotid artery MRA, typical software phantom as used in our experiment. *Bottom*, from *left* to *right*: zoom on thickness error, zoom on veering error. A series of *yellow points* connected through a *yellow line* indicates the pathline, and the *brown* mesh indicates the segmentation

two interesting questions that this comparison may answer: can we gain a better understanding of how users use the two views if they have to couple them manually, and how much time does the manual coupling really take for this relatively simple kind of navigation? As regards COUP versus AXIS, we expect rotation to be an important visual cue for aiding interpretation; therefore, the availability of free rotation weighs against further reduction in DOF. One of the goals of this experiment is to see how this works out.

Image data set

Vascular structures are relatively easy to model as software phantoms, see for example Rolland et al. [17]. The software phantoms we use in this study were developed in conjunction with the LUMC image processing division and were used in several other studies [19–21]. Software phantoms make it easy to generate dozens of cases with an unambiguous ground truth and similar difficulty levels. So, we artificially generated the MRA images, along with segmentations with artificially generated segmentation errors. The phantoms are made so as to match the complexity of real MRA data of the carotid artery and abdominal aorta.

Real blood vessels are often highly curved, and many may be found in a single MRA scan. We constructed each phantom vessel image using a random sum of sine functions. Three distractor vessels were added in each phantom. We matched the size of the volume ($128 \times 128 \times 128$) and the thickness of the vessels (around 6 pixels thick) with that with our real abdominal aorta data. Thickness of each vessel varies in a stylized manner with normal and thinner areas. When looking at a radial cross-section, density in the center of the vessel is highest, gradually lowering towards the boundaries of the vessel, and zero outside of the vessel. No noise or other distractors were added, neither were bifurcations present. See Fig. 2.

In our task, segmentation errors are defined as a deviation between the segmentation and the densest parts of the volume. This is actually a simplification of real clinical data, but makes the task easier to understand and less ambiguous. Only three error types exist: the segmentation veering away from the vessel, the segmentation being thinner than the vessel (the vessel data retains its thickness while the segmentation is around 50% thinner), and the segmentation being thicker (the segmentation retains its thickness while the vessel data shows around 50% reduction in thickness). See again Fig. 2.

Controls

Control is mouse-based only. In FREE, movement relative to the view is accomplished by holding the middle mouse button (MMB), which effectively results in dragging the model with the mouse. The mouse wheel is used to move the camera forwards and backwards.

In pathline-based navigation, the camera is always centered around a point on the pathline (called the *focus point*) and is rotated so that the vessel is viewed from its side. The pathline is navigated by rolling the mouse wheel or by clicking on a pathline point with the middle mouse button (MMB). In case the DVR and CPR focus points are not coupled, the individual focus points can be changed by moving the mouse over the corresponding view. At the start of each trial, the initial focus point is set in the middle of the vessel, that is, on the pathline point that is in the middle of the vessel's array of pathline points.

If user rotation is enabled, the user can specify rotation using a standard two-axis valuator control [4], controlled with the right mouse button (RMB). In free navigation, this is absolute rotation. In pathline-based navigation, it is relative to the vessel's angle. In CPR, the RMB can be used to rotate around the vessel axis by moving the mouse vertically.

Additionally, the user can zoom in and out with a fourth button on the left side of the mouse (LSMB), as found on the standard Microsoft Intellimouse. Both views can be zoomed in and out independently. The initial zoom level is moderate, providing some overview of the vessel, and requiring some zooming in to see the actual details well.

A pathline point can be selected or deselected with the left mouse button (LMB). Points within a rectangular area can be selected using a standard area selection scheme. When the mouse is moved while holding the LMB, a rectangle appears that can be dragged to cover the desired points. The appropriate points are highlighted in green. Area deselection can be done by selecting an area with only already-selected points in it.

Experimental setup

Like Moise et al. [11], we evaluated our system with medical laypersons. We make the assumption that the results can be transferred to medical experts. Because our task and software phantoms are somewhat simplified, medical laypersons could easily perform the experiment and had little trouble understanding the "ground truth". Our experience with user studies on 3D visualization involving both laypersons and medical experts is that both perform comparable 3D tasks similarly (i.e. [28]).

We recruited 12 unpaid subjects from the Human Media Interaction department of our CS faculty. By recruiting mostly Ph.D. students and a few Ph.Ds from the CS faculty, we chose the laypersons to have an educational level comparable to that of the medical experts. We also ensured the subjects were in an appropriate age range, ranging from 25 to 51 years, with an average of 32, and 2 users above 40. While only four users were women, our experience in the medical domain also indicates a majority of men there.

The subjects participated in two experiments in a single session: a visualization experiment, involving CPR and DVR as single-view visualizations, and the navigation experiment described here. Both experiments took about 30 min to complete each. The visualization experiment is not further described here, but we can say that the exposure to CPR and DVR meant users required less training for the navigation experiment. The navigation experiment was introduced by a 5-min interactive tutorial explaining the different navigation modes. The users were hinted that using both visualizations will increase accuracy. The sessions were conducted in a quiet room, with the users seated at a distance of about 70 cm from the 24″ display. An experimenter was seated behind them.

We used a within-subjects design: each user was exposed to all conditions. There are 4 conditions. Each user performed 2 trials for each condition, so s/he performed $4 \times 2 = 8$ trials total. All users received the same set of software phantoms in the same order. This ensured that the difficulty level of the phantoms did not vary among users. The conditions were randomly ordered and counterbalanced. The relative positions of the two trials for each condition were counterbalanced so as to reduce learning effects. At the end of each trial, time taken and number of errors made were recorded and shown to the user, before the next trial began.

Before the experiment, the users had to fill in a form with some demographic questions. After the experiment, the users were asked to fill in a subjective survey. For the subjective survey, we used standard five-point scales, following this pattern:

Question: "Did you prefer condition *X* or condition *Y*?". The answer scales: (1)—strongly prefer condition *X*, (2)—somewhat prefer condition *X*, (3)—do not prefer either condition *X* or *Y*, (4)—somewhat prefer condition *Y*, (5)—strongly prefer condition *Y*.

In the subjective survey, the users were asked about their preferred interaction methods as regards the following items:

- *freepos*: free camera movement versus camera movement using the focus point. (1) = strongly prefer focus point movement …(5) = strongly prefer free movement.
- *coupled*: single focus point versus one focus point per view. (1) = from strongly prefer single focus point …(5) = to strongly prefer one focus point per view.
- *freerot*: free rotation versus only rotation around vessel axis. (1) = strongly prefer rotation around vessel axis only …(5) = strongly prefer free rotation.
- *areasel*: selection of points using area selection versus selecting points one by one (1) = strongly prefer one-by-one centerpoint selection …(5) = to strongly prefer area selection.

– *wheelnav*: moving focus point using mouse wheel versus selecting focus point using middle mouse button. (1) = strongly prefer MMB navigation …(5) = strongly prefer mouse wheel navigation.
– *cprusage*: usage of the two (CPR and 3D) views. (1) = I used the DVR view almost all of the time …(5) = I used the CPR view almost all of the time.

Additionally, they were asked general questions about the overall user interface. In particular, two questions about animation smoothness and clarity of detail, and four questions about control sensitivity. These were meant for diagnostic purposes.

Results

In this section, we will interpret the experimental data, that is, the user performance, the subjective survey results, and the "raw" interaction data. We will start with a short validation of the data. In the main results section, we will examine the users' time and error performance, and their subjective preferences. In the interaction data section, we will examine what users were actually doing during the interactions.

Most interactions appeared to go smoothly without serious user interface problems or misconceptions. Some users made slips in the controls, in particular pressing the wrong mouse button for a particular action. Mostly these had little impact on performance.

The overall user interface survey indicated the basic interaction was satisfactory. Only two users reported minor problems for animation smoothness or clarity of detail, and all other users found the computer graphics quite satisfactory. As regards control sensitivity, most users found it "just right". For each control that was asked about, only 1–3 users found it "a little too sensitive".

Main results

We will first examine time performance. We can expect time performance effects to be multiplicative rather than additive, so we transformed the data using the log transform. We used a second transformation to increase statistical sensitivity. It is based on the fact that the sequence of software phantoms used for the trials was the same for all users. We divided the time for each trial by the overall average of that trial over all users (note that all conditions occurred equally often for each trial in the sequence). This has the effect of normalizing for variations in phantom difficulty.

We performed a repeated-measures ANOVA on the four conditions, which yields $F(3, 33) = 25.3$, $P < 0.0005$, meaning that the conditions are significantly different. A Sidak post hoc analysis reveals that AXIS and COUP perform significantly faster than both FREE or UNCOUP ($P < 0.047$, except that AXIS is only tentatively faster than UNCOUP ($P = 0.11$). UNCOUP is also significantly faster than FREE ($P = 0.013$). Average time performance is given in Table 1. This suggests that FREE is clearly slowest, followed by UNCOUP, followed by AXIS and COUP.

Table 1 Performance statistics

Condition	FREE	UNCOUP	COUP	AXIS
Average time (s)	174.3	122.7	101.5	101.7
Average error rate	8.88	7.54	7.54	7.08

Table 2 Subjective variable statistics

Variable	Nr. users					Average
	1	2	3	4	5	
Freepos	9	2	1	–	–	1.33
Coupled	10	1	1	–	–	1.25
Freerot	2	–	1	4	5	3.83
Cprusage	1	3	2	4	1	3.09
Areasel	–	1	3	6	2	3.75
Wheelnav	1	1	1	2	7	4.08

Number of users who selected each item on each survey scale, and the average value

Error rate is defined as the number of selected pathline points that do not match the "correct" error regions, which may include both false positives (the user selected too many) and negatives (the user selected too few). Repeated-measures ANOVA over the four conditions is not significant ($F(3, 33) = 1.135$, $P = 0.349$). Differences between average error rates per condition are not very large either, see Table 1. To summarize, there are only small differences in error rate, and while error rate seems a little higher in FREE (18% to be exact), the difference is not significant.

For the subjective results, see Table 2. Most users strongly preferred the pathline-based and coupled navigation conditions. Most users also preferred the ability to rotate freely, but results were less clear-cut; two users even strongly dispreferred free rotation. Usage of the two views was equally divided, with one user almost always using CPR and one almost always DVR, and the rest of the users somewhere in-between. We conclude that subjective results mostly match performance results.

The two subjective variables areasel and wheelnav indicate more general usability aspects of the user interface. We see that users mostly preferred area selection over point selection, but not strongly, which is consistent with the fact that most users did use both types of selection. As regards navigation, most users strongly preferred wheel navigation, though some users dispreferred it. We shall examine the possible causes of these differences in the next section.

Interaction data

In this section, we also analyze the interaction data, both quantitatively and qualitatively. This enables us to gain some qualitative insight into the interaction patterns, though we would need a larger follow-up study with more users to obtain quantitative results. Quantitative data includes time spent using mouse wheel and MMB during each trial, and time spent rotating and zooming during each trial. We use absolute times (in seconds) and relative times (time spent doing an action as relative to the total trial time).

Users used CPR and DVR differently. Many would select items primarily in either DVR or CPR. Others would navigate primarily in either. Sometimes the view a user used for selection was different from the one used for navigation, and sometimes it was obvious that the user used both views even though s/he interacted with only one. This indicates that "clickstream" type interaction data is not always a good indication of when which views were used by the user. The FREE and UNCOUP conditions are possible exceptions. UNCOUP has more or less symmetrical navigation, which gives us the best indication of how often the users really use both views. We measured the relative time spent navigating either view in UNCOUP. We found only two trials where a user only navigated the DVR view (these were from different users); both views were navigated in all other trials. The average relative time spent navigating was 66% in DVR and 34% in CPR.

Users spent only an average of 0.96 s. per trial on zooming, and 0.6 s. on rotating around the view axis, which is 0.67% of the average trial time. In contrast, they spent around 21.4 s.(9.1% of the time) on rotating around the other two axes using the RMB. Additionally, it was almost always used when available. This indicates that the RMB rotation control is the most important control w.r.t. rotation and zooming.

Two users made remarks about confusing rotation around strong bends in the pathline. There appear to be two problems: strong rotation of the model during navigation and inconvenient view angles when the focus point is on a bend. The latter will be worse in the AXIS condition, because such angles cannot be corrected by the user.

One apparent problem with free rotation is that the user can accidentally produce counterintuitive orientations. One of the worst cases is when the DVR is rotated so that the vessel is facing in exactly the opposite direction as the CPR. If you move the CPR right, the DVR will move left. Some users accidentally encountered these situations.

Most users manually coupled the two views in UNCOUP and FREE, by first navigating one view and then navigating the other to match the first. One user gave up coupling in one trial and used the DVR view only for the rest of the trial; one gave up coupling in FREE and used CPR only for both FREE trials. One user developed an alternative technique without coupling: first do coarse selection of all errors in CPR, then refine them in DVR. In FREE, one user would use the zoomed-out CPR to orient himself in the DVR.

Most users used both area and single-point selection. Typical was first selecting an area, then fine-tuning the selection by selecting/deselecting single points. Two users mostly used point selection. One of them is the user who dispreferred areasel in the subjective survey. One of the users and a third user remarked that an axis-oriented rectangular area was a mismatch for the orientation of the vessel in DVR. This suggests that an area selection mechanism that is oriented in the direction of the closest vessel pathline is better.

Most users used the mouse wheel almost exclusively, while the MMB navigation was used little. Some users used the MMB to position the focus point on one end of the vessel at the beginning of the trial; one user commented that the two controls were useful for different situations. However, two users used the MMB most of the time instead of the wheel. The two users are the only ones who ever used the MMB more than 4 times in any single trial. The average of all other users was less than one click per trial. If we look at subjective preference (wheelnav), we find that almost all users prefer the wheel, and these two users were the only ones who dispreferred it. We asked the two MMB users about their preference. One said that with the MMB it was possible to indicate an absolute direction. We also observed that some users forgot which way to turn the wheel to go back or forward: that is, they forgot whether forward translates to left or to right. We conclude that the choice between MMB and mouse wheel was a personal preference, which probably depended on the user's need to indicate an absolute direction explicitly.

Discussion

The results mostly corresponded to our initial hypotheses, though we found indications of trade-offs for each of the different navigation choices.

Comparing FREE against the other restricted-DOF conditions, we can conclude that FREE performs much worse. Classic problems of free navigation, such as confusion of controls and "getting lost", could be observed. Overall time performance was much slower than the other conditions. Error performance was also worse, but not significantly so. We did find one possible advantage of free navigation, which is that navigation is done in an absolute direction. We found that some users preferred specifying an absolute direction rather than the relative direction specified by the mouse wheel. However, there are other ways to specify absolute direction (in our case, using the MMB to click on a centerline point).

As regards the coupled (COUP and AXIS) versus UNCOUP conditions, we observed that most users coupled manually if automatic coupling was not available. This was probably what caused it to perform 20% slower than the coupled conditions. No difference in error performance was measured. Users strongly preferred the coupled conditions as well. We also found that users actually use both views most of the time.

For the COUP versus AXIS conditions, the average time and error performance were almost equal. Users were however strongly divided, with a majority strongly preferring COUP and a minority strongly dispreferring it. The strength of opinion might indicate that some users have trouble with either of the conditions. The analysis of the interaction data indicated several potential problems. One is that rotation is very strong and has inconvenient angles around strong bends in the pathline, which is probably worse in AXIS because it cannot be corrected. This can be remedied by smoothing the rotation angles. Another is that free relative rotation can produce counterintuitive angles, in particular one view moving in the opposite direction of the other. This is especially important since we found other indications that users could lose their sense of orientation. This could be remedied by restricting the rotation to limited angles.

Besides this study of conditions, we also found some issues that suggest some general user interface recommendations. One is that a coupled view with the mouse wheel is probably best shown vertically, so that it corresponds to vertical scrolling as regularly done by the mouse wheel. Another is that area selection best follows the vessel's angle, instead of being oriented along the view axis.

Conclusions

We examined a technique for navigating a computer-based dual CPR–DVR visualization, based on the existence of a pathline, which has not yet been studied. By choosing one particular point on the pathline as point of reference, rotation and position of both views can be matched, and 3D navigation can be reduced to only 2 DOF total for the dual visualization. We performed a user study with medical laypersons, who had to perform a visual search task to find segmentation errors. The study compared our proposed technique to several variants, including more traditional forms of navigation.

We found that the restricted and coupled navigation performs significantly better than free and uncoupled navigation, and as good as coupled navigation where users could specify free relative rotation in DVR. This suggests the choice of very restricted DOF successfully makes navigation easier without being too restrictive. We did however find that restricted navigation with free rotation performed equally well and that users were strongly divided over which of the two techniques was best. Our observations of user interactions indicated several potential usability problems that could be addressed. This suggests further directions for user studies, in particular evaluating improved versions of rotation restrictions.

Our study has its limitations because we used laypersons and somewhat simplified software phantoms. In order to further examine and verify our findings, future studies will require clinicians working with either real data or more faithfully modeled software phantoms. Of the simplifications we made (in particular no noise, no bifurcations, thickness variation is stylized, and segmentation errors are simplified), we believe that in particular the modeling of thickness variation and segmentation errors are relevant. The simplified versions served well to reduce "ground truth" determination problems for laypersons. With clinicians, however, a more faithful modeling of these is needed in order to validate the experiment properly.

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