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DOI

[10.5220/0001797804050408](https://doi.org/10.5220/0001797804050408)

Publication date

2009

Document Version

Author accepted manuscript

Published in

GRAPP 2009

[Link to publication](#)

Citation for published version (APA):

van Schooten, B. W., van Dijk, E. M. A. G., Zudilova-Seinstra, E. V., de Koning, P. J. H., & Reiber, J. H. C. (2009). Evaluating visualisation and navigation techniques for interpretation of MRA data. In A. Ranchordas, J. Madeiras Pereira, & P. Richard (Eds.), *GRAPP 2009: proceedings of the Fourth International Conference on Computer Graphics Theory and Applications, Lisboa, Portugal, February 5-8, 2009* (pp. 405-408). INSTICC Press. <https://doi.org/10.5220/0001797804050408>

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EVALUATING VISUALISATION AND NAVIGATION TECHNIQUES FOR INTERPRETATION OF MRA DATA

A Taxonomy and Experimental Framework

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Keywords: volume visualization, 3D navigation, radiology, MRA

Abstract: We argue that a more systematic treatment of the many existing options for medical volume visualisation is desirable. We show that combining the most common medical visualisation and navigation techniques in a systematic way leads to a meaningful set of interesting and sometimes novel UI techniques. We evaluate these UI techniques qualitatively to arrive at a set of promising techniques for future research. We also propose that user experiments can be more easily conducted using an experimental framework which incorporates all of these techniques, and enables the use of generated data and non-medical users for conducting user experiments.

1 Introduction

Computer-aided medical volume interpretation is an emergent discipline, for which user interfaces (UIs) are still designed in a rather ad hoc way. Therefore we argue that a more systematic approach to the subject is desirable. We will propose a first version of such an approach here for the domain of vascular structures, as obtained by MRA (magnetic resonance angiography). Our approach includes a taxonomy of UI techniques, and makes it easier to do systematic user experiments to test and compare UI techniques for particular tasks.

The tasks we will focus on are MRA interpretation tasks done by medical experts. This typically involves verification of automatic analyses of the vascular structures (Zudilova and Sloot, 2005), in particular the vessel centerline (describing a curved line going through a particular vessel), and vessel segmentation (describing the surface of a particular vessel).

We will distinguish several aspects of visualisation and navigation, and define a set of commonly occurring options for each. We then illustrate that different combinations of these options result in a set of meaningful and sometimes novel UIs, many of which are worth evaluating experimentally. We are implementing a visualisation engine that handles all of these techniques.

Evaluating UIs often involves doing extensive user experiments. In the case of medical UIs, the medical expertise required for performing real-life medical tasks typically makes it difficult to find enough subjects. Additionally, making available suitable medical data with appropriate expert interpretations is also quite a challenge. We argue that, at least for the exploratory phases of UI research, these problems can be circumvented by appropriate computer-generated data, and adapting task design to non-experts, removing the need for both medical experts and medical data. In a later research phase, the most promising UIs can then be evaluated with experts and/or real data.

Evaluating medical UIs with non-medical users using tasks adapted for non-experts is an interesting approach that is elaborated on only occasionally in the literature (Moise et al., 2005). The problem is how to ensure that the results are still valid for real medical situations. We argue that this is possible, and techniques for ensuring validity are worth studying further. It can be done for example by limiting the experiments to general or basic conditions only, by evaluating the tasks in some way with medical experts, and by varying task parameters to obtain information about how the results can be extrapolated to variations of such tasks.

As part of the visualisation engine, we imple-

mented a 3D data and problem generation algorithm, which enables us to evaluate any UIs immediately for a given task. We present a qualitative overview of all UIs in our taxonomy, based on a qualitative analysis using our visualisation engine.

2 Task and model

The 3D models that we work with are 3D greyscale volumes. Typical sizes for MRA scans are $128 \times 128 \times 64$ - $512 \times 512 \times 512$ voxels. We are interested in user interpretation of the output of a typical automated vessel analysis tool, in particular centerlines and vessel wall segmentations. A centerline is a 3D curved line segment that is supposed to follow the inside of a vessel (though it does not always need to be in the center). A segmentation consists of a 3D surface mesh that corresponds closely to the vessel wall, and is generated based on the centerline.

Errors can occur in these automated analyses, which will have to be detected by a medical expert. A centerline can only veer away from the actual vessel location. A segmentation can be erroneous in more ways: it can also become too wide or narrow, for example by following bifurcations or vessels that are too close to tell apart by the algorithm.

We designed an algorithm for generating vascular-like structures, and generating mock automatic analyses with artificially introduced errors. MRA results in relatively clean and easy to model data, so this is a relatively easy task as compared to other medical volumes. Vessels are generated by painting in the volume with a 3D “brush” following random sine-like functions. For one generated vessel (the “focus” vessel) a centerline and/or segmentation is generated. Errors are then introduced artificially, by making the centerline or segmentation veer away or otherwise deviate from the vessel at particular locations. The user task will be to point out the locations of the errors (not correct them).

In the current generation algorithm, the concept of “inside” and “outside” of the vessel is a simplified one, so that non-medical people will be able to perform the task. In particular, the vessel is always defined by a nicely cylinder-shaped high-density region in the volume. Bifurcations can also be included in the vessel, in which case the centerline and segmentation follows only one of the branches. Next to the focus vessel, distractor vessels can be generated.

The most important difference with real-life data is that the hardest to interpret vessels are not nicely shaped, and the highest-density areas do not always correspond to the location of the vessel. This is roughly the range of problems for which medical expertise is

required. Still, what we *can* test with this simplified model is how well basic interpretation tasks can be done, such as overall structure interpretation, and inspection of a particular detail or error. Incorporating data that reflects real-life data more closely, for evaluating with experts only, can be considered a topic of future research.

3 Visualisation

The most commonly used MRA visualisations are described below; see also figure 1. First we have the **slice** visualisations, only showing a slice of the data:

- **cross-section** - shows the volume data that intersects an arbitrary plane. One particular cross-section that is often used is a close-up cross-section of the vessel at a particular point on the centerline. Other kinds of cross-sections are less suited for data that is as sparsely filled as vascular data, since most of them will show up as empty space with a few dots. So, we do not consider them here.
- **CPR** (Curved Planar Reformatting) (Kanitsar, 2004) - a curved cross-section following the curvature of the vessel. It is especially suited for vascular structures, as it reveals properties and local context of a particular vessel much more clearly than a non-curved one can. Optionally, the cross-section can be distorted topologically so that the vessel shows up as a straight line.

Secondly we have the **volume** visualisations showing the entire volume:

- **DVR** (Direct Volume Rendering) (Mueller et al., 2005). This involves rendering the volume as a semi-transparent 3D object, representing the greyscale values as densities. Various enhancements exist, such as shading and colour mapping.
- **isosurface** (Preim and Oeltze, 2007). This involves converting the greyscale volume to a surface by connecting the points which have a particular greyscale value. The result is a plain mesh, which is relatively easy to interpret visually, enabling clear occlusion cues and shading. A lot of the data is lost in this visualisation, however. It is in fact likely that isosurface, by itself, is unsuited to most of our real-life interpretation tasks.
- **MIP** (Maximum Intensity Projection) (Preim and Oeltze, 2007). This involves creating a 2D projection in which each pixel value is the brightest value found in a ray cast into the scene from that point. Unlike DVR or isosurface, there is no visual cue indicating which parts of the visible structure are in front or behind others.

Figure 1: Top left: CPR with centerline. Top right: DVR. Bottom left: isosurface with segmentation and centerline. Bottom right: MIP with centerline.

In cross-section and CPR, the centerline can be shown by projecting it onto the cross-section surface, and the segmentation is typically shown by only showing the lines that intersect the cross-section plane. In the 3D and MIP views, both centerline and segmentation can be shown in an obvious manner. Additionally, occlusion cues can be used for displaying centerline and segmentation. Isosurface enables the easiest occlusion cues, but they are also possible with properly thresholded DVR. With a bit of creativity they can also be included in the slice views, to show where the centerline or segmentation is in front or behind the sliced plane.

It is also possible to combine multiple visualisations by integrating them into a combined visualisation. After considering all combinations of the five basic visualisations, we came up with the combinations below (see also figure 2). As far as we know, these combinations form novel medical visualisation techniques, except the volume-volume combination.

- **isosurface-slice** - isosurface with any slice visualisation as integrated 3D figure. To compensate for the incompleteness of isosurface data, it may make sense to integrate an isosurface view with a slice visualisation, drawing the slice as an oriented plane in the 3D view. The isosurface helps visualise the overall vascular structure, while the slice view enables viewing of greyscale details (see for example (Gavidia Simonetti et al., 2004) for a similar proposal using two separate visualisations). Note that isosurface-CPR results in a curved slice passing through the centerline (see figure 2 for an example).
- **CPR-volume** - CPR with any volume visualisation, with the volume view simply drawn over the CPR. A particular centerline point is chosen for which both views are made to coincide graphi-

cally. Additionally, the orientation of the 3D view around the centerpoint is equal to that of the CPR. This coincides with centerline-based navigation and flyby rotation methods. In case the 3D occludes the CPR in an inconvenient way, they can be displayed one below the other.

- **volume-volume** - any volume visualisation with any volume visualisation. One visualisation is drawn regularly, one or more others are drawn as oriented planes inside the main visualisation. For example, there may be three separate oriented planes on the back faces of the cube surrounding the rendered volume. This type of visualisation is used by the QMRADWI application (de Koning et al., 2003) developed at Leiden University medical center (LUMC).
- **isosurface-DVR** - isosurface with DVR as integrated 3D figure.

Figure 2: Top left: isosurface-CPR. Top right: CPR-isosurface. Bottom left: volume-volume (DVR-MIP). Bottom right: isosurface-DVR.

4 Navigation

Designing appropriate navigation techniques can be difficult and needs to be studied separately. For 2D representations, navigation consists of panning and zooming. For 3D representations, this includes 6 degrees of freedom (6 DOF) camera manipulation, plus optional zooming. The 6 DOF can be separated into 3 DOF positioning and 3 DOF rotation. The number of DOF is an important aspect, as more DOF places increasing demands on the navigation method or input device used (i.e. (Zhai, 1998)).

We distinguish several common types of (position) navigation:

1. **centerline-based navigation**: the user can cycle through the points of the centerline forwards and

backwards. The view is centered around the currently selected centerline point (the focus point). This is typically used as the navigation method for CPR, but it can also be used for navigating in 3D. In 2D, this only leaves zooming as a degree of freedom. In CPR, this leaves 1 additional DOF, namely rotation around the vessel axis. In 3D, this leaves 3 additional DOF, namely, free 3D rotation.

2. free navigation: The position can be determined freely rather than being fixed to a centerline point. In 2D and CPR, we can now freely pan horizontally and vertically. In 3D, we now get 6 DOF.
3. pickray navigation: A coordinate is selected by clicking on the centerline or vessel wall. The camera will navigate to the selected point. Here we make use of the fact that the problem setting is quite suitable for pickray techniques. This method is not applicable to 2D and CPR. In 3D, this leaves again the 3 DOF of rotation.

Rotation in 3D can be treated separately. There are several obvious options:

1. free rotation angle
2. rotation angle always follows angle of centerline. This is a relatively novel navigation technique for MRA. There are several interesting visualisations that can be achieved using this method. Because free rotation is required to select a point to be picked, this method is not compatible with pickray selection.
 - flythrough: If the camera is oriented parallel to the centerline, and we zoom in close, you get a “flythrough” of the vessel (similar to a cross-section view of the vessel). This is a generalisation of a common visualisation method, also known as virtual endoscopy or virtual angiography (Giachetti et al., 2001; Bartz and Straer, 1999), which is usually based on the segmentation.
 - flyby: If the camera is oriented perpendicular to the centerline, you look at the vessel from “above” (similar to a CPR view of that part of the vessel). We will call this a “flyby” view of the vessel. It is essential that the user is able to rotate around the vessel axis to get a good view of the vessel from all sides.
3. rotation angle follows angle of centerline, but the user can specify a free relative rotation angle.

5 Qualitative analysis of the UIs

We have now covered a number of aspects of the task, model, and UI, and have enumerated a number

Figure 3: Left: flyby / DVR. Right: flythrough / isosurface.

of common options for each. We also covered interactions between the options qualitatively.

A complete setting (combining task and UI) is obtained by making a choice for each aspect. However, not all settings are equally appropriate, and in this section we give a qualitative analysis of which UIs are promising for which tasks. Even while we do not have user data, qualitative issues (which features are well visible or not visible at all in a particular situation?) are one type of issue that we can already address here, with help of our visualisation engine.

We analysed each combination of task and visualisation method in a systematic way. For each visualisation, we considered the following tasks:

- Interpreting the overall 3D structure and locating a particular vessel in 3D space (**overview**).
- Viewing fine greyscale details at relevant locations around the centerline and segmentation (**greyscale**).
- Seeing deviations of the centerline (**deviate C**) and segmentation (**deviate S**) from the greyscale data.

The results are found in table 2. For each case, a rating was given in the range *not possible* to *excellent*, and we tried to summarise what kind of navigation was necessary to perform the task.

Additionally, we summarise all possible combinations of rotation and position navigation in table 1. The table summarises which ones are valid and useful, and how many DOF each requires.

6 Conclusions and future research

Based on table 2, our general findings for visualisation techniques can be summarised as follows: The most promising technique for the overview task is volume-volume. For the greyscale task these are CPR, CPR-volume, and cross-section. For the deviation tasks they are CPR, CPR-volume and possibly isosurface. The most promising visualisation techniques overall are isosurface-slice and CPR-volume, both of which are novel techniques. Isosurface also

Table 1: Table summarising all navigation types and their decomposition into different degrees of freedom. The valid types are given in boldface. Legend: *1D*, *2D*, *3D*: positioning in resp. 1,2,3 dimensions; *rot*: 3DOF rotation; *axis*: 1DOF rotation around vessel axis. Note that zooming is possible and useful in all cases, and adds one extra DOF to the total.

visualisation → position↓ rotation→	3D				cross-section (none)	CPR (axis)
Free	3D + rot	not useful	not useful	not useful	2D	2D + axis
Centerline	1D + rot	1D + rot	1D + axis	1D	1D	1D + axis
Pickray	2D + rot	pick confusing	cannot pick	cannot pick	N/A	N/A

has some potential, though it is not clear yet if it is valid for real-life tasks.

We found that occlusion cues generally make errors easier to find. They help show the user when a centerline or segmentation is in front of or behind a vessel in volume visualisations (otherwise, it is only possible to see if the centerline is beside a vessel, and rotation is necessary to reveal the other situations). The cues will be less effective if distractor vessels are in the way. This means that, the more distractors, the less potential the occlusion cues have. We also found that, while centerline occlusion cues are possible in CPR, we found they are not necessary.

Our findings for navigation techniques can be summarised as follows. Free 3D positioning results in a total of 7 DOF (6 DOF + zooming), which will be relatively difficult to control and may require a special input device. Centerline or pickray based navigation neatly circumvents this problem. Centerline-based position navigation has the broadest application range, as it can be used for all combinations of visualisations and rotations, for most of which it is a relatively novel navigation technique. This may make it easier to work with multiple visualisations corresponding to different aspects of the same model. It also results in the fewest DOF. Pickray navigation is also promising, but is only useful in combination with free 3D rotation.

Some of the most interesting UIs are formed using flyby and flythrough navigation. We found that flythrough (i.e. virtual angioscopy) is conceptually something like a cross-section with additional context, and shows local deviations of centerline or segmentation relatively clearly. However, it works best with isosurface, and less well with DVR or isosurface-DVR, which obscures some of the details. For flythrough, isosurface-slice appears to be a promising visualisation technique. Flyby navigation also has potential to show local deviations well, and appears to work better with DVR than flythrough. Flyby is also inherent in CPR-volume.

Overall, these results point out some promising and novel alternatives, and in this way, this attempt at systematic coverage of UI options seems successful.

ACKNOWLEDGEMENTS

This research is funded by the NWO/VIEW project “A Multi-modal Visualization Environment for Interactive Analysis of Medical Data” (N 643.100.602).

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Table 2: Table summarising all visualisations. Legend: Task type: C=centerline; S=segmentation. Occlusion cues: C=centerline or S=segmentation. Navigation type: F=free, C=centerline-based, P=pickray. Rotation type: F=free, C=follow-centerline, B=flyby, T=flythrough.

visualisation	3D cues	navigation	rotation
cross-section	C –	F C –	– C – –
overview:	not possible		
greyscale:	good, extensive centerline-based navigation required.		
deviate:	excellent for both C and S, however, extensive centerline-based navigation required.		
CPR	C –	F C –	– C – –
overview:	poor, rotation around vessel axis required		
greyscale:	good, rotation around vessel axis required		
deviate C:	excellent, error can be seen immediately as a veering away or gap in the vessel		
deviate S:	good, only for too-wide or too-narrow type errors, rotation around vessel axis required		
DVR	C S	F C P	F C B T
overview:	fair, little navigation required		
greyscale:	fair, rotating and zooming required		
deviate:	fair, rotating and zooming required		
isosurface	C S	F C P	F C B T
overview:	good, little navigation required		
greyscale:	not possible		
deviate C:	excellent, occlusion cues help see if the centerline is in front of or behind the vessel, so little navigation required		
deviate S:	good if isosurface is representative of the segmentation location, rotating and zooming required		
MIP	– –	F C P	F C B T
overview:	fair, rotation required, sometimes hard to see what's in front or behind		
greyscale:	fair, rotating and zooming required		
deviate:	fair, rotating and zooming required		
isosurface-slice	C S	F C P	F C B T
overview:	fair, little navigation required. For CPR, the slice plane may make visual scene harder to interpret		
greyscale:	good. Requires close-up view and centerline-based navigation.		
deviate C:	excellent, occlusion cues help see if the centerline is in front of or behind the vessel, so little navigation required		
deviate S:	good if isosurface is representative of the segmentation location, navigation required		
CPR-volume	C S	– C –	– – B –
overview:	fair, little navigation required		
greyscale:	good, navigation same as particular volume visualisation method		
deviate:	good to excellent, similar to CPR		
volume-volume	C S	F C P	F C B T
overview:	excellent, the cube backface projections help locate a point precisely		
greyscale:	fair, rotating and zooming required		
deviate:	fair to excellent, inherits properties from both visualisation methods used		
isosurface-DVR	C S	F C P	F C B T
overview:	good, little navigation required		
greyscale:	fair, though not as good as DVR by itself, rotating and zooming required		
deviate:	good, similar to isosurface, though not as good.		