Supporting Depth and Motion Perception in Medical Volume Data

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There are many application areas where dynamic visualization techniques cannot be used and the user can only view a still image. Perceiving depth and understanding spatio-temporal relations from a single still image are challenging tasks. We present visualization techniques which support the user in perceiving depth information from 3D angiography images, and techniques which depict motion inherent in time-varying medical volume datasets. In both cases no dynamic visualization is required.

1 Introduction

Volume rendering has become a mature field of interactive 3D computer graphics. It supports professionals from different domains when exploring volume datasets, representing for example medical or meteorologic structures and processes. Current medical scanners produce datasets having a high spatial resolution, and even dynamic datasets can be obtained. Especially Computer Tomography (CT) datasets are highly suitable for showing anatomical structures. However, when dynamic processes have to be explored a single 3D volume dataset is often insufficient. For example, Positron Emission Tomography (PET) imaging techniques are used for exploring the dynamics of metabolism. Successive scans produce a time series of images each showing the distribution of molecules at a certain point in time. Time-varying volume data is also produced when applying functional Magnetic Resonance (MR) imaging techniques to evaluate neurological reaction to certain stimuli.

Although 3D volumes can be displayed separately to view the data for specific points in time, the dynamics contained in a time-varying dataset can only be extracted when considering all of them. Therefore time-varying volume datasets are often visualized by displaying the 3D volumes sequentially in the order they have been acquired. When rendering these 3D volumes at a high frame rate, the viewer is able to construct a mental image of the dynamics. Besides the possibility to acquire time-dependent data also the spatial resolution of medical scanners has been increased leading to large and possibly more complex datasets. This complexity demands the development of interactive visualization techniques supporting an efficient and effective analysis. Since the medical datasets acquired through different imaging technologies differ in the way they are explored, specialized techniques have to be developed. We propose visualization techniques which have been developed to support the exploration of angiography datasets. We will show how the depth perception and thus the spatial cognition of these datasets can be improved and thus results in a more efficient as well as effective diagnosis.

Often dynamics are used to visualize both time-varying as well as high resolution datasets. In the latter case rotations or other interactive techniques are applied to explore the datasets. However, in some domains these techniques are inappropriate, since viewers prefer still images rather than dynamic image sequences. The following two problems arise when dealing with image sequences of 3D volumes. When several people watch an image sequence, a viewer usually points at a specific feature within an image to exchange findings with the other participants. Since the images are dynamic, it is hard to pinpoint such an item of interest, especially if it is moving, and the animation needs to be paused. Another problem is the exchange of visualization results. In medical departments diagnostic findings are often exchanged on *static media* such as film or paper. However, it is not possible to exchange time-varying volume datasets in this manner. Although the sequential viewing process could be simulated by showing all 3D volumes next to each other, this could lead to registration problems, i.e., it would be more difficult to identify a reference item across the 3D volumes.

We address these problems by proposing visualization techniques which represent the motion dynamics extracted from a time series of 3D volumes within a single static image and support the exploration of high resolution datasets. All presented techniques are implemented in our Volume Rendering Engine *Voreen* [Vor07].

2 Related Work

Depicting Motion

Mainly non-photorealistic rendering techniques are used for depicting motion in a single image. Masuch et al. [MSR99] present an approach to visualize motion extracted from polygonal data by speedlines, repeatedly drawn contours and arrows; different line styles and other stylization give the viewer the impression of a hand-drawing. Nienhaus and Döllner [ND05] present a technique to extract motion information from a behavior graph, which represents events and animation processes. Their system automatically creates cartoon-like graphical representations. Joshi and Rheingans [JR05] use speedlines and flow ribbons to visualize motion in volume datasets. However, their approach handles only feature extraction data and is mainly demonstrated on experimental datasets. Meyer-Spradow et al. [MRVH06] use speedlines to visualize motion dynamics extracted in a pre-processing step. Furthermore they use edge detection and transparency techniques to show several time steps in one still image.

A lot of research in the area of dynamic volume visualization has been dedicated to flow visualization. Motion arrows are widely used [LHD*04], but are often difficult to understand because information is lost when performing a 2D projection to the screen. Boring and Pang [BP96] tried to tackle this problem by highlighting arrows, which point in a direction specified by the user. Texture based approaches compute dense representations of flow and visualize it [MCD92]. First introduced for 2D flow, it has also been used for 3D flow visualization, for example with volume line integral convolution used by Interrante and Grosch [IG97]. Svakhine et al. [SJE05] emulate traditional flow illustration techniques and interactive simulation of Schlieren photography.

Hanson and Cross [HC93] present an approach to visualize surfaces and volumes embedded in four-dimensional space. Therefore they use 4D illuminated surface rendering with 4D shading and occlusion coding. Woodring et al. [WWS03] interpret time-varying datasets as four-dimensional data fields and provide an intuitive user interface to specify 4D hyperplanes, which are rendered with different techniques. Ji et al. [JSW03] extract time-varying isosurfaces and interval volumes considering 4D data directly.

Supporting Depth Perception

The most common technique used for visualizing vessel structures is the maximum intensity projection (MIP). In contrast to this direct rendering technique, model-based approaches generate and visualize a model of the vessel system to support generation of high quality images. The initial work on this topic has been done by Gerig et al. in 1993 [GKS*93]. Hahn et al. [HPSP01] describe an image processing pipeline to extract models of vascular structures in order to generate high quality visualizations. In 2002 Kanitsar et al. [KFW*02] have proposed a model-based visualization technique based on curved planar reformation. Oeltze and Preim [OP05] have introduced in 2005 the usage of convolution surfaces to further enhance visualization quality especially at vessel furcations. While all other techniques focus on visualizing the vessel structures without contextual information, the VesselGlyph provides also context information given by surrounding tissue [SCC*04].

In this paper we use monoscopic visualization techniques to enhance depth perception. We do not discuss monoscopic depth cues in detail, for an overview we refer to the work done by Lipton [Lip97] and Pfautz [Pfa00]. A detailed comparison of the influence of depth cues on depth perception is described by Wanger [WFG92]. Ropinski et al. [RSH06] propose and compare different kinds of depth cues. Different models have been proposed for evaluating the interplay of depth cues. These models consider combinations of different depth

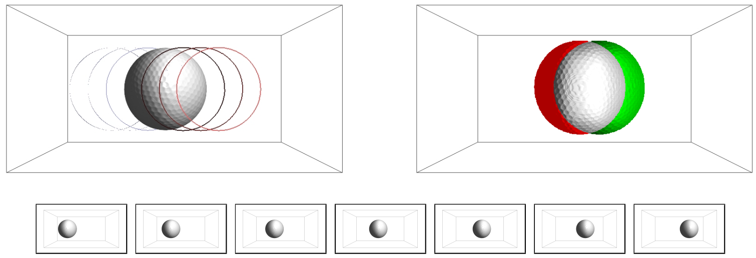

Fig. 1. Two visualization techniques to depict the motion of the golf ball volume dataset. The current 3D volume is rendered using isosurface shading. Edges of preceding and succeeding 3D volumes are shown (*left*); the combinations of the current and the succeeding 3D volumes are rendered with different colors (*right*). Renderings of seven time steps extracted from the dataset (*bottom*).

cues and postulate how these depth cues contribute to the overall depth perception. The models incorporate for instance the weighted linear sum [BC88], a geometric sum [DSW86], or the reliability of depth cues in the context of other cues and additional information [YLM93].

3 Illustrating Dynamics

We visualize the motion dynamics that is inherent in a volume dataset in a single static image which is constructed from the images of the dataset at succeeding points in time. We distinguish three groups of 3D volumes, depending on their points in time. The current volume is used as a reference. The second group contains the chronologically preceding volumes, and the third group the chronologically succeeding ones.

The current volume is rendered using a direct volume rendering (DVR) technique. The resulting image contributes most to the final image and is then enriched with information gained from the other two groups. For the visualization of these groups we propose two techniques: edge detection and color coding of differences between the volumes. The parameterization is based on the difference in time between the current and the preceding/succeeding volumes. In comparison to using motion blur these techniques have the advantage that they avoid blurring information contained in the images.

For the edge detection technique we first render the current time step with DVR. We also use DVR to render all preceding/succeeding volumes we are interested in. On the resulting images we use an image based edge detection by applying an appropriate filter kernel. Thus we receive the silhouettes of the preceding/succeeding volumes. We use an edge threshold (by considering the lengths of gradients) to show only edges exceeding a certain thickness. The color of the edges depends on the point in time of the corresponding volume.

These parameters can be chosen freely. For the example in Figure 1 (*left*) we used cold colors for the edges of the preceding and warm colors for the edges of the succeeding volumes. In addition, the edge threshold for preceding volumes depends on their point in time so that older volumes are depicted with thinner edges. In a final step the individual images need to be composed into a single image as final result. This can be done by either blending the images or masking them by considering the background color.

The color coding technique shows the differences between two time steps. Both time steps are rendered using DVR. Then three sets of pixels are distinguished: the pixels determined by

- the image of the current volume,
- the image of the succeeding volume, and
- the intersection of the images.

For the intersection the user has to decide in which time step he is more interested in. This set of pixels will then be shown as is. For the other two sets only the brightness information is used and multiplied with a color, for instance red for the current volume and green for the succeeding one. This ensures that the alpha-part of a transfer function can be used. Finally the three disjoint sets are blended into the final image as can be seen in Figure 1 (*right*).

4 Depth Enhancement

Because of the complex depth structure of angiography datasets spatial cognition is one of the most challenging tasks during their exploration. We introduce techniques to support the user in recognizing the depth structure of vessels even in static images while the user concentrates on regions he is interested in, and we try to minimize the visualization of unwanted information that may distract him.

4.1 Depth-Based Mouse Cursor Replacement

In most desktop applications a computer mouse together with its screen representation is used. Usually the screen representation is an arrow-shaped cursor that is used to point at certain locations of interest or to interact with objects. We alter this representation and provide additional depth information with the mouse cursor.

The user is not only interested in one depth value, but would like to compare depth values at different positions, e.g., which of two vessels is closer and which is farther away. For this purpose we use a so called cross-hair cursor instead of the standard cursor. A cross-hair cursor consists of two orthogonal lines, which are parallel to the x- resp. y-axis. Their intersection point corresponds to the original mouse cursor position, and the cross-hair moves with

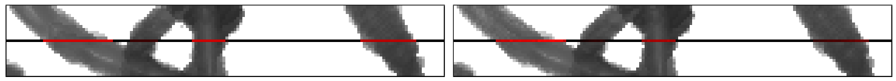

Fig. 2. Color coding of the depth structure. The detail images show the differences when using an absolute mapping (*left*) and a relative mapping (*right*). In the left image the right vessel seems to have the same depth value as the left ones. The right image show that actually the right vessel is further away from the observer.

the mouse. To show different depth values simultaneously we use a depth-dependent color coding for every point of the cross-hair cursor. The color of such a point is chosen according to the depth value at its position. Since vessel visualization commonly uses gray shades only, color coding for visualizing additional information can be applied without any drawbacks.

The cross-hair is colored in real time while the user moves with the mouse over the angiography image. The remaining image stays untouched. As the cross-hair is moved by the mouse, the user can control the two perpendicular lines easily and exploit their color to compare the depth of different vessels. Once he finds an interesting constellation where the cross-hair cursor shows the relevant information, he can make, e.g., a printout for further use.

Coding schemes

A color scheme maps the range of depth values in a one-to-one manner to different colors, for example a red to black gradient. Then parts of the vessels covered by the cursor which are closer to the viewer will be colored in bright red shades, when the user moves the cross-hair over them, and vessels which are farther away will be colored using a darker red or black. Such a mapping scheme has the advantage that the same color always represents the same depth value. But it also has a drawback: Angiography images may contain many depth values from a relatively large depth range. Mapping the depth values in a one-to-one manner to colors may result in very small and hard to detect color nuances (see Figure 2 (*left*)). This problem can be addressed by choosing not only a red to black gradient, but using the whole color spectrum. But it can be further improved.

Preliminary tests have indicated that users prefer to compare vessels lying on the cross-hair lines without moving the cursor. Hence it is possible to show the user not only small absolute differences, but also larger relative differences (see Figure 2 (*right*)). To do this we count the number of different depth values covered by both lines of the current cross-hair cursor and divide the available color interval into the same number of subintervals before mapping every depth value to a color. As a (simplified) example assume that the cross-hair cursor crosses three vessels with the (normalized) depth values 0.7, 0.9 and 0.8, and these values should be visualized with a red to black gradient. In this case the gradient will be divided into three intervals—bright red, dark red,

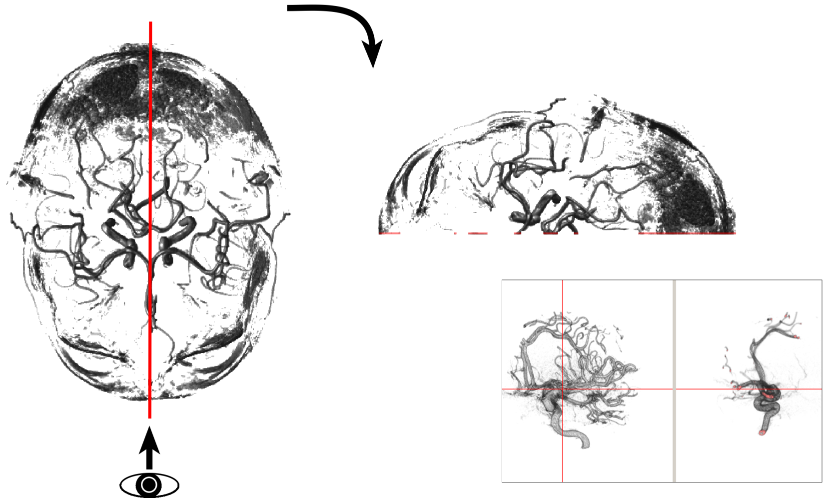

Fig. 3. The splitview seen from bird's eye view and an example what the user sees (small image bottom right). The right view shows the vessel structure in a side view. The current slice is marked red, and the front region is clipped.

and black—and the cross-hair will be colored with these different colors at the appropriate locations. This also works with many different depth values in such an intervall, because values near 0.7 will still be visualized very dark and values near 0.9 will still be shown as a bright red. In case of an absolute mapping all values would have been mapped to slightly different shades of dark red.

Of course in some situations with a large amount of widespread depth values the proposed mapping yields only a small advantage, but in most cases it enhances the visualization. Especially when applied to the very sparse angiography datasets it is easy to find an appropriate mapping. However, the user has to be aware of the fact that the color coding is only valid within one position of the cross-hair cursor, because the current depth range may change when the cursor is moved. The use of a gradient with more than two colors may further improve the visualization.

4.2 Splitview Visualization

Another intuitive way to perceive depth information is to change the viewing position in order to look from the left or from the right. But when switching the viewing position the user may get disoriented within the vessel structure. Showing both views simultaneously solves this problem. Therefore we use a multi-view visualization with linked cameras and some extensions. Usually the user is not interested in a side view of the whole vessel structure but concentrates on some details in the image. Therefore we divide the vessel structure into two parts, and in the side view we visualize only the part being in focus (see Figure 3). Looking from the front we cut along a plane that is determined by two vectors: the first vector points from the viewer's eye to the mouse cursor, the second is the up vector. This results in a vertical plane that divides the vessel structure in a left and a right part. In the side view only the left part is visualized, i.e., the parts of the vessel structure being behind the cutting plane. The cutting plane and the side view are calculated and visualized in real time, so the user can alter the view with the mouse and see the result immediately.

To illustrate vessels that cross the cutting plane, the intersections are marked with red color. To clarify the relation between both views we use a cross-hair cursor whose horizontal line is continued through the side view. Furthermore this line makes it easier for the user to orient herself. This technique needs a short familiarization, but has two big advantages: the user can perceive depth relations immediately, and also very small depth differences are clearly visible.

5 Application Examples

5.1 Heart Motion

We have used a segmented time-varying volume dataset of the human heart to test our visualization techniques. First we have applied our techniques to different time steps of the same slice. In Figure 4 (*left*) we use direct volume rendering to display one time step and silhouette rendering, i.e. edge detection, for the other time steps. In Figure 4 (*right*) the differences between two time steps are visualized with different colors. The *succeeding only* pixels are colored with red shades, and the *current only* pixels with green shades. In the *intersection* the pixels of the original image of the current dataset are shown.

Both techniques are suitable for visualizing motion of a complete volume by displaying all slices simultaneously; the slices can be arranged for instance in a checker-board pattern physicians are familiar with.

In Figure 5 we add some additional context information to the rendering. We have cut the dataset with a clipping plane. In addition we rendered some of the surrounding organs using tone shading. To achieve an impression similar to visualizations used in medical illustrations we added a rendering of the body's silhouette.

5.2 Vessel Visualization

We have applied both techniques for enhancing depth perception to an angiography dataset. Without any depth cues it is nearly impossible to figure

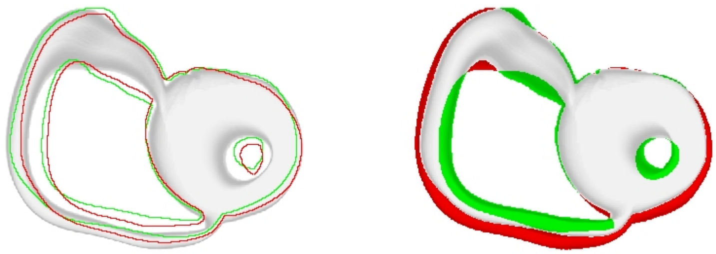

Fig. 4. Visualization of heart motion. Edges of preceding and succeeding volumes are shown (*left*). Differences between two time steps are color coded (*right*).

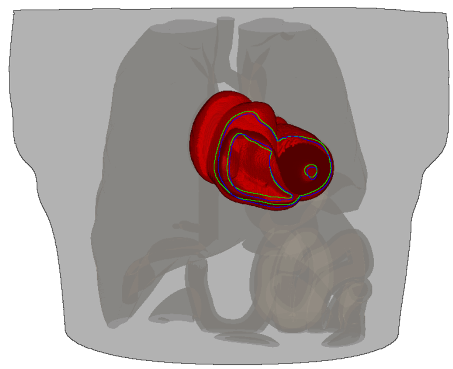

Fig. 5. Context information added to the visualization of heart motion.

out the exact depth structure of the vessels (see Figure 6 (*left*)). The color coding of depth values with the cross-hair allows spatial cognition. A gradient from red over green and yellow to blue is used for the depth coding, using red for near structures and blue for those farther away.

The cross-hair visualization is very suitable for depth structures of medium complexity but not sufficient for more complex ones, because for every pixel only the nearest structure is visible. In such cases the split view visualization works well (see Figure 6 (*right*)). In the left view a front perspective of the vessels is shown, in the right part a side view. All structures lying in the right half of the left view are cut away for the side view. Thus the precise depth structure of the plane determined by the vertical line of the cross-hair and the viewing direction is visible in the right view. To further improve the side view, structures cutting the plane are colored red.

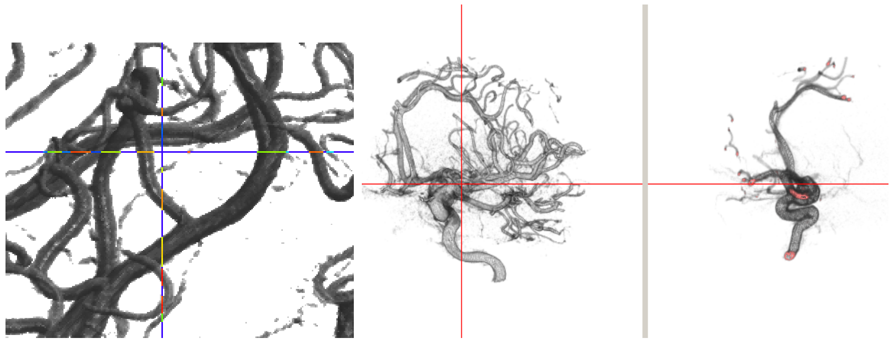

Fig. 6. The cross-hair cursor visualizes depth information (*left*). Here a mapping to a rainbow gradient is used. The splitview (*right*) shows a front view of the vessels in its left part and a sideview in the right part. Structures lying in the right half of the front view are cut away in the side view.

User Study

The results of a survey evaluating the usage of interactive techniques and the techniques described above as well as further discussions with physicians have indicated that users prefer to view interactive visualizations over static ones. But as stated above, interactive exploration is often not possible. And especially medical visualization experts also appreciated the cross-hair cursor, which shows additional information even in a static view.

On a five-point Likert-scale, where 1 corresponds to not helpful, and 5 corresponds to very helpful, participants assessed the feature of being able to rotate the vessel structures with 4.73 on average. Medical experts rated the cross-hair cursor with 4.5 (color gradient) and 4.0 (red gradient); non-experts assessed these techniques as not beneficial (color gradient: 2.5, red gradient: 2.0). However, many participants especially used the horizontal line of the cross-hair in order to evaluate depth using a scan line analogue.

Independent of the experience with medical visualization, nearly all participating users have evaluated the splitview visualization as very helpful (on average 4.5). In particular the reddish cutting slice in the right view (see Figure 6 (*right*)) has been evaluated as very helpful (in average 4.73). Although we assumed that the usage as well as interpretation of the result of this technique requires some effort to get used to it, the users remarked that after a short period of practice the handling is intuitive instead of complex.

6 Conclusions and Future Work

In this paper we have presented visualization techniques for depicting dynamics and depth characteristics in still renderings of (time-varying) volume datasets. The techniques are applied automatically and do not need any user input. In order to obtain interactive frame rates they have been implemented as extensions to GPU-based ray-casting. To demonstrate the usability of our visualization techniques we have described the application to real world data.

With the techniques presented in the first part it is possible to present a reasonable subset of the motion information contained in a time-varying dataset in a single image. Thus this information can be communicated more easily since it can also be visualized on static media. The techniques to improve depth perception enable the user to build a precise mental image of depth structures even for very complex data.

To get further directions we have conducted informal interviews with physicians which work with angiography datasets. These interviews have revealed that in addition to the interactive rotation of a dataset in order to better perceive its depth relation, the possibility to switch between combinations of different perspectives is very welcome.

Another open issue is the development of an appropriate lighting model which improves spatial comprehension in angiography. While in general the phong lighting model was preferred to the tone-based color coding, the highlights were perceived as distracting. Therefore it would be necessary to evaluate in how far existing lighting models are able to give shape cues without tampering the depth perception.

7 Acknowledgments

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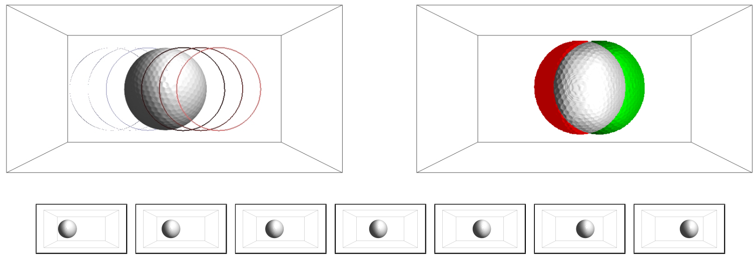

Fig. 7. Two visualization techniques to depict the motion of the golf ball volume dataset. The current 3D volume is rendered using isosurface shading. Edges of preceding and succeeding 3D volumes are shown (*left*); the combinations of the current and the succeeding 3D volumes are rendered with different colors (*right*). Renderings of seven time steps extracted from the dataset (*bottom*).

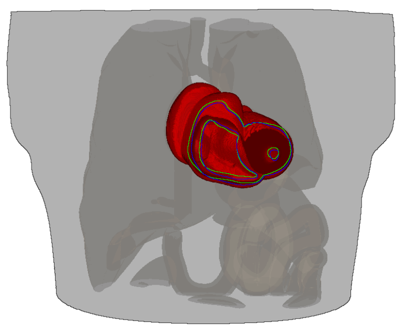

Fig. 8. Context information added to the visualization of heart motion.

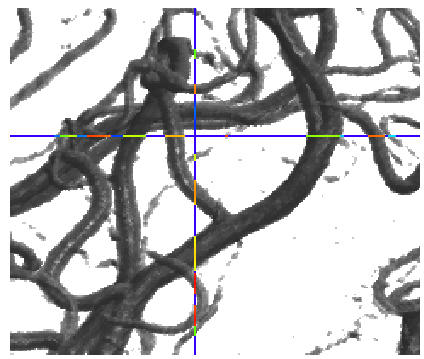

Fig. 9. The cross-hair cursor visualizes depth information. Here a mapping to a rainbow gradient is used.

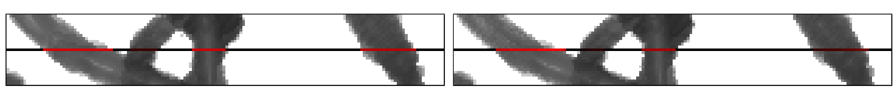

Fig. 10. Color coding of the depth structure. The detail images show the differences when using an absolute mapping (*left*) and a relative mapping (*right*). In the left image the right vessel seems to have the same depth value as the left ones. The right image show that actually the right vessel is further away from the observer.