Illustrative Visualization of Vascular Models for Static 2D Representations

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Abstract. Depth assessment of 3D vascular models visualized on 2D displays is often difficult, especially in complex workspace conditions such as in the operating room. To address these limitations, we propose a new visualization technique for 3D vascular models. Our technique is tailored to static monoscopic 2D representations, as they are often used during surgery. To improve depth assessment, we propose a combination of supporting lines, view-aligned quads, and illustrative shadows. In addition, a hatching scheme that uses different line styles depending on a distance measure is applied to encode vascular shape as well as the distance to tumors. The resulting visualization can be displayed on monoscopic 2D monitors and on 2D printouts without the requirement to use color or intensity gradients. A qualitative study with 15 participants and a quantitative study with 50 participants confirm that the proposed visualization technique significantly improves depth assessment of complex 3D vascular models.

Keywords: Line and Curve Generation, Visualization, Evaluation, Planning and Image Guidance of Interventions

1 Introduction

During surgery it is often important to understand the morphology of vascular structures and its spatial relation to surrounding risk structures such as tumors. Therefore, high-quality vascular 3D models, reconstructed from CT, are applied using direct or indirect volume rendering techniques. The vascular models often portray complex geometries and therefore demand cognitive effort and user interaction. Physicians request a visualization technique that can encode essential information such as the location, spatialness, and distances to important anatomical structures. The ideal solution might be to provide one or more static images that encode all relevant information at a glance. These static images might be printed out or displayed on a monitor in order to provide decision support during surgery.

The work of Ritter et al. [7] is closest to our work and is guided by a similar set of requirements and application scenarios. They evaluated non-photorealistic rendering techniques for vascular structures and showed that these techniques facilitate shape and depth assessment. Wang et al. [10] presented a method for depth perception on interventional X-ray images. They improved the rendering scheme and used depth cues that

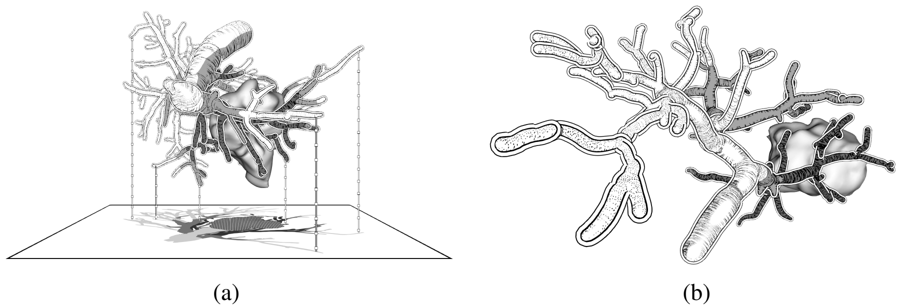

Fig. 1. Our visualization technique applied to hepatic vasculature with a tumor obtained by using [3]. In (a), we use illustrative shadows, supporting lines, and contours as depth cues. In (b), different hatching styles and a decent gray tone emphasize vessels at risk around the tumor.

preserve the original X-ray intensities. Furthermore, methods for depth-based color-coding were proposed, e.g., pseudo-chromadepth by Ropinski et al. [9]. Kersten-Oertel et al. [4] investigated the effect of different perceptual cues for vascular volume visualization and showed that pseudo-chromadepth cues were stronger cues than stereopsis. Because color-coding of depth is not always applicable (e.g. printouts or AR projections on the organ surface) a color-sparse representation of spatial information would be beneficial. We propose a visualization technique that uses as few colors as possible, see Fig. 1. To assess the benefit of our visualization technique, we performed a qualitative study. In addition, a subsequent quantitative study compared our approach with Phong shading [6] and pseudo-chromadepth rendering [9], as it was rated best of different depth cues in previous studies, c.f. [4, 9].

2 Method

To improve depth assessment of 3D vascular models, we present a combination of illustrative shadows, supporting lines and view-aligned quads. A hatching scheme that uses different stroke styles depending on a distance measure is described.
• *Illustrative shadows:* Inspired by Ritter et al. [8], we employed illustrative shadows. For this, we placed a plane under the vascular model. The position of the plane is determined by the center point of the vascular model and it is shifted along the up-vector of the camera such that it does not intersect the model. The up-vector of the camera serves also as the normal of the plane. Afterwards, we place a camera on the opposite direction of the plane to create shadows by an orthographic projection. Frame buffer objects were used to save the scene of the camera and to texture the underlying plane. For the vessel shadows, we use the same grey values as for distance encoding between vessel and tumor in the 3D model in order to illustrate the spatial relations on the plane. We apply hatched strokes to emphasize the projected tumor.
• *Supporting Lines:* As an additional depth cue and reference for the shadows, we introduce supporting lines. Here, we used the idea by Glueck et al. [2] to generate lines from the objects of interest to the plane. The medical expert can select a point on the

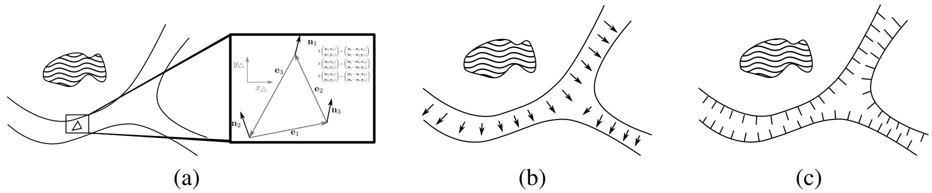

Fig. 2. Overview of the *ConFIS* method. In the first step, the curvature tensor per triangle is determined, see (a). This is used to calculate the principle curvature directions per vertex, see (b). Afterwards, the streamlines are determined, see (c).

surface by picking, and a supporting line is generated that connects the point and the corresponding intersection point of the plane. Along the line, a view-aligned quad is provided. On this quad, we generate texture coordinates to draw a ruler-like illustration. Finally, we generate (x,y) coordinates, where x represents the width of the quad and y lies in the range $[0, L_{line}]$ with L_{line} representing the length of the quad and starting from the plane with $y = 0$. The ruler-like illustration may serve as an indicator for the distance to the plane. Here, we draw a white line with a black contour such that it can be perceived independent of the background color. Therefore, if x lies in a margin around zero, the fragments are drawn white, and for a larger margin, the black color is used. Conceptually, we generated the coordinate system (x,y) by:

$$x' = \text{fract}(d \cdot x) - 0.5, \quad y' = d \cdot y, \tag{1}$$

where fract computes the fractional part of the argument and d is a value that specifies how many glyphs are drawn in the interval $[0,1]$. Then, the coordinate system can be used to draw white squares with a black contour around it. The ruler-like supporting lines can also be used for precise depth comparisons. The more squares are under the back line of the plane, the closer is the corresponding point.

• *Depth-Dependent Contour:* To further support depth assessment, we utilized a depth-dependent halo contour inspired by Bruckner and Gröller [1]. First, we determine the shading by multiplying the normals of the vascular with the view vector. We use these values as a scalar field: $\varphi = \langle \mathbf{n}, \mathbf{v} \rangle$, where $\mathbf{n}$ is the normal and $\mathbf{v}$ is the normalized view vector. Afterwards, we determine the position of the zero-crossing of φ on the edges per triangle, which are denoted by $\mathbf{p}_i$ and $\mathbf{p}_{i+1}$. Finally, we use these positions to generate a view-aligned quad with their endpoints $\mathbf{p}_{out1/2/3/4}$ in the *Geometry Shader*. For this, we use the *width* as well as the normal vector at the zero-crossing:

$$\mathbf{p}_{out1/2} = \mathbf{p}_i \pm width \cdot \mathbf{n}_i, \quad \mathbf{p}_{out3/4} = \mathbf{p}_{i+1} \pm width \cdot \mathbf{n}_{i+1}. \tag{2}$$

Note that $\mathbf{n}_i$ is the interpolated and normalized normal vector of the triangle at the zero-crossing at position $\mathbf{p}_i$. As vascular models are usually based on world space coordinates, the perceived thickness of the contour is a measure for the distance between vessel and camera position. For this purpose, we linearized the *depth* ranging from 0 to 1 in the near and far plane. Afterwards, the *width* is computed by: $width = 2 \cdot (1 - depth^2)$. This allows a better assessment of the depth by using quadratic function.

• *Shape Cues and Distance Encoding:* To provide recognizable shape cues, we employed the *ConFIS* method by Lawonn et al. [5], see Fig. 2 for an overview of this method. The distance of the vascular structure to the tumor determines the strokes of the streamlines. Therefore, we need to determine the distances of the vascular structures to the tumor. As the tumor is given as a triangulated surface mesh, the triangles of the tumor are used to generate an infinite prism along the normal. Then, we iterate over the generated prisms of the tumor and test if the vertices of the vascular structure lie inside the prism. If this is the case, we determine the distance of the triangle with the vertex. Furthermore, we calculate the distance between the vessel vertices and the tumor vertices. Finally, we compare all distances and associate the shortest distance to the vertex of the vessel. This yields tessellation-independent distances of the vascular structure with the tumor.

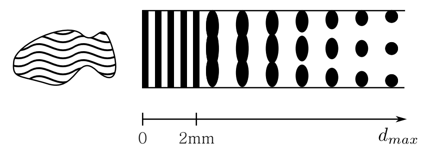

Fig. 3. For the risk zones, streamlines are used for illustration. The more distant from the tumor the more the α increases.

To enhance vessel parts at risk zones, we alter the *ConFIS* visualization at potentially affected vessels. Instead of generating streamlines, we generated quads as described in Eq. 2 with a corresponding coordinate system (recall Eq. 1). Then, we use implicit ellipses which are drawn on the quad: $\alpha \cdot x'^2 + y'^2 \leq r^2$. Whenever this inequality is fulfilled, the fragments are drawn, where r specifies the radius and α is a distance-dependent value that describes the width of the ellipse. The values of α are set as:

$$\alpha(dist) = \begin{cases} 0 & \text{if } dist \leq 2mm \\ \frac{dist}{dist_{max}} & \text{otherwise,} \end{cases}$$

where $dist$ describes the distance from the tumor and $dist_{max}$ is the maximum distance. We used 2mm as a threshold as this describes the risk zone and set α such that the streamlines are fully drawn at the risk zone. In addition, the glyphs continuously change from ellipses to circles depending on the distance to the tumor, see Fig. 3.

• *Evaluation:* To assess our visualization concept, we started with a *qualitative study*. The study was performed with 10 researchers who are familiar with medical visualization and 5 physicians with a focus on surgery. First, we showed the subjects our visualization technique with different vascular models. Then, they could explore the model, until they were ready for the next task. Second, we explained them our new visualization technique and showed them how to place the supporting lines. Finally, we presented 12 printed scenes with 3D vascular models rendered using our approach. The models were generated out of 6 liver CT datasets including 12 vascular trees – portal vein and hepatic vein for each dataset. In addition, red points were placed on different branches of each tree. We presented the scenes to the subjects and asked them to order the labeled branches according to the distance from the viewing plane, and asked them how they assessed the distances.

Based on the results of the qualitative evaluation, we conducted a *quantitative study* using a web-based questionnaire. Because in [4], pseudo-chromadepth rendering was

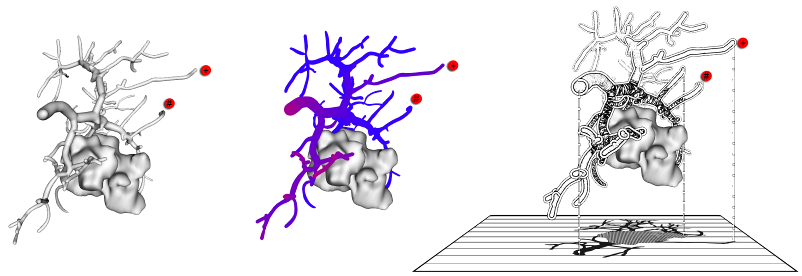

Fig. 4. A scene with a tumor and liver vessel is illustrated using different renderings styles. From left to right: Phong shading, pseudo-chromadepth, and our technique.

rated as the best depth cue for vascular visualization, we compared our illustrative visualization technique with pseudo-chromadepth rendering [9], and Phong shading [6] (no explicit depth cue). Our subject pool consists of 50 subjects (19 female, 31 male, age M=30.9y, range 17-48y). 24 subjects are computer scientists, others are physicians (8), engineers (6), natural scientists (5), and others (7). Most of them (31) have no experience with vascular visualizations.

To probe the subjects assessment of relative depth distances, we designed 24 tasks that require a precise judgment of depth. For each task, subjects had to sort the correct depth order of two labeled branches, see Fig. 4. The models were presented to the subjects in pseudo-randomized order to minimize learning effects. Because we wanted to assess the effect of our illustration technique, 8 visualizations of vascular models using the new techniques had to be compared with 8 pseudo-chromadepth renderings and 8 Phong renderings of the same model identical in every major aspect, except for the display algorithm. We defined four conditions: FF, FN, NF, and NN to specify the positions of the labels, where F means *far* and N means *near*. The first capital describes the pixels' distance of the labeled branches in the image space. We consider the maximum distance D connecting branches that are furthest away from each other. If the distance d of the labeled branches fulfills $d < \frac{D}{2}$ then it is defined as N, otherwise as F. For the second capital we use the z distance of the near and far plane. If the z distance of the labeled branches is greater than half of the distance of the far and near plane it is denoted as F, otherwise as N.

The quantitative investigation included a training phase, in which all 3 modalities were explained and subjects were asked to perform two test tasks (not included in the evaluation) for each modality. They were also informed that time is measured after the training phase. After completing a task, subjects were asked to rate their confidence on a 5-point Likert confidence scale where 5 means very confident and 1 very unconfident, and to press a button to start the next task.

3 Results

In the *qualitative study*, subjects stated that a mix of illustrative shadows and supporting lines was the most useful combination. Contours were rarely used, as the differences in width were hard to perceive. Three subjects stated that the contour supports a spatial impression and supports the depth assessment, but it depends on the distance of labeled branches. If the points were placed on supporting lines the subjects could order the depth correctly. Four subjects asked for a grid on the floor to easily see the intersection point of the supporting line with the plane. They stated that this would enhance and fasten the sorting process of the supporting lines. We added this feature for the quantitative study. If no supporting lines were placed, the result strongly depends on the complexity of the vascular tree. Therefore, the more complex the vascular structure the more supporting lines are needed to assess the correct depth.

For the *quantitative study*, the data was analyzed by a 3 (visualization techniques: illustrative, pseudo-chromadepth, and Phong) $\times$ 2 (*xy* distance: F far, N near) $\times$ 2 (z distance: F far, N near) ANOVA for repeated measurements (see Table 1 for the statistical results).

Table 1. ANOVA results of different effects.

*p <0.05 and **p <0.01			Assessment		Confidence		Time	
Effect	df1	df2	F	η^2	F	η^2	F	η^2
Visualization techniques	2	98	93.25**	.66	118.61**	.71	16.71**	.25
xy distances	1	49	22.86**	.32	.77	.02	2.62	.05
z distances	1	49	27.31**	.36	110.43**	.69	1.90	.04
Visualization techniques $*$ *xy*	2	98	4.42*	.08	7.05**	.13	.37	.01
Visualization techniques $*$ z	2	98	20.16**	.29	85.94**	.64	2.00	.04
xy $*$ z	1	49	.03	.00	12.92**	.21	4.12*	.08
Visualization techniques $*$ *xy* $*$ z	2	98	2.12	.04	16.38**	.25	28.38**	.37

• *Distance Assessment:* Subjects were able to assess the relative distances more precisely with the illustrative visualization, followed by pseudo-chromadepth (Fig. 5). The given answers for Phong seem to be randomly; only $\approx$48% of the distance estimation tasks were performed correctly. With Phong, subjects achieved better results when the distance in the *xy* plane was small. For the illustrative visualization, the same but weaker effect could be assumed, while for pseudo-chromadepth rendering the *xy* distance seems to have no effect. The opposite effect was observed for z distance: while subjects could perform the pseudo-chromadepth tasks significantly better in case the z distance was large, this effect was not observed for Phong and the illustrative visualization.
• *Confidence:* Subjects were most confident with the illustrative visualization, followed by pseudo-chromadepth, and most unconfident with Phong (Fig. 6). They were more confident with conditions FF and NF. The significant triple interaction shows, that subjects are most confident with condition FF using illustrative visualization or pseudo-chromadepth, and condition NN using illustrative visualization. Subjects were most unconfident with condition NN using pseudo-chromadepth, and with Phong in general.
• *Time:* As shown in Fig. 7, subjects decided significantly faster using pseudo-chromadepth (M = 10.95 s), followed by Phong (M = 13.21 s) and illustrative visualization (M = 14.04 s). Particularly, the FN condition seems to be difficult and delays decisions (M = 13.95 s), while for all other conditions subjects needed approximately the same

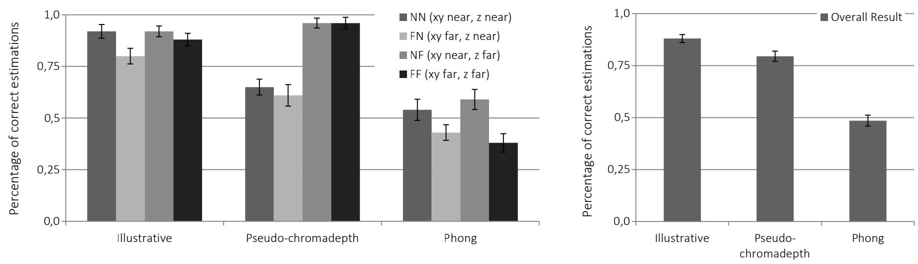

Fig. 5. Results for the distance estimation on a scale from 0 (false) to 1 (right). The errors bars represent the standard error.

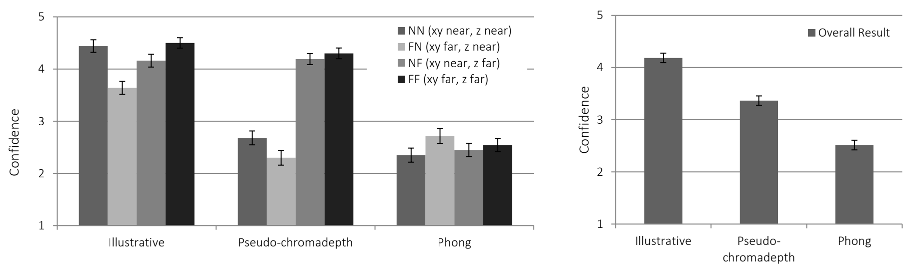

Fig. 6. Confidence rated on a 5-point Likert scale (5 = very confident, 1 = very unconfident). The errors bars represent the standard error.

amount of time. The significant triple interaction seems to be caused by conditions FN and NF which are the best for pseudo-chromadepth and worst for illustrative, while NN and FF are approximately equal for all visualization techniques.

4 Discussion

Illustrative visualization has a high potential to improve the spatial perception of complex vascular models. The proposed visualization method provides strong monocular depth cues without the requirement of a medium able to display color and intensity gradients. However, color coding can be used to encode additional information. Especially if relative distances between vascular structures are small, supporting lines and illustrative shadows are a great help to perceive the depth.

According to the results of the qualitative study, the depth-dependent contour was rarely used, as differences in contour width were hard to perceive. The contour might not be the main depth cue when illustrative shadows and supporting lines are available. One idea was to use the contour to encode additional information, e.g., instead of using a white contour, color-coding can be applied to encode distances. However, contours can yield a false assessment of vessel diameters which might be critical in some cases.

Regarding our qualitative study, we made minor alterations and conducted a web-based quantitative evaluation with 50 subjects. The results prove that our new technique enhances depth assessment of vascular models for static 2D representations. Our approach leads to more correct depth assessments compared to pseudo-chromadepth

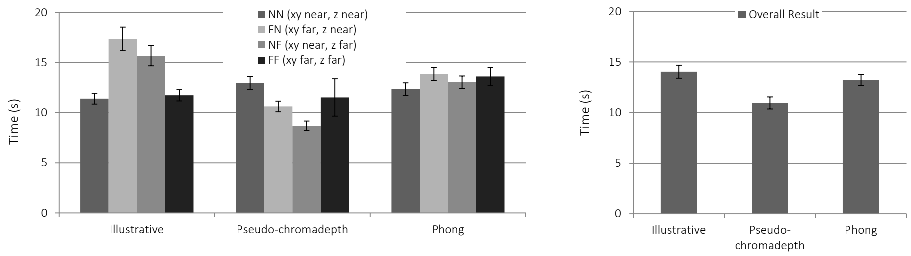

Fig. 7. Time for task completion. The errors bars represent the standard error.

rendering which was rated best in previous studies [4, 9]. Moreover, the subjects were even more confident in their decision. As a drawback, the subjects needed more time to assess the depth of the illustrative technique. This is because the supporting lines and the shadows need more cognitive effort to map from the 3D scene to the plane. Therefore, it is a tradeoff between a fast depth assessment and a correct estimation.

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