Evaluating vascular visualization methods for pre-operative planning in the mesentery

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Abstract

In this thesis I evaluate and compare a selection of vascular visualization methods with the help of surgeons. Vessel topology is highly varied, and individuals may have extra or "missing" branches, changes in connectivity, or changes in which vessel goes over or beneath another vessel. Visualizing these structures is highly relevant for surgeons preparing for surgery. While direct volume visualization methods can quickly produce accurate but noisy images, indirect volume visualization methods produce clean images at the cost of a laborious and potentially error-prone segmentation process. By comparing the visualizations methods, interviewing and doing task comparisons with surgeons, I investigate the clinical viability, advantages, and disadvantages of these methods.

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Chapter 1

Introduction

In this chapter, I first discuss the motivation behind this thesis. Then I discuss my objectives and the main contribution of this work before finally presenting an outline of the thesis.

1.1 Motivation

Surgeons at the Haukeland University Hospital and Haraldsplass are interested in having an easy way to reconstruct 3D arteries and veins for optimal surgical planning when preparing for surgery. In order to surgically remove colorectal pancreatic cancer, several blood vessels need to be clamped or moved aside in advance in order to ensure minimal bleeding. However, this process is complicated by the diverse and varied topology of the human vascular system. Blood vessels present in one person is not necessarily present in another, or they can be above or beneath different vessels.

Currently, surgeons either go in blind or make sketches based on slice images acquired using Computer Tomography (CT) scans of their patients, as existing solutions tend to require either time-consuming manual segmentation or do not sufficiently convey the complex topology of arteries and veins crossing one another. They have noted that their manual sketches are often quite inaccurate, and after initial visualization experiments proved promising, they are now interested in more modern visualization methods in order to enter surgery more prepared.

1.2 Objectives

My main objective with this thesis is to evaluate vascular visualization methods for pre-operative planning. The two main approaches are model-based rendering using a segmented model, and direct volume rendering. Ideally these visualizations should require minimal manual effort on the part of the user, so that surgeons can quickly come to a good quality visualization without detailed training on how to use the tools. My hypothesis is that the clean images of model-based indirect volume rendering (IVR) methods may be preferred by surgeons over images produced by direct volume rendering (DVR) methods. However, the reduced ambiguity and potential errors introduced in the segmentation process required by IVR might lead to a false confidence in given answers. To test this hypothesis, I aim to:

1. Implement several commonly proposed vascular visualization techniques to form a basis for a user study using different visualization methods.
2. Perform a short user study with surgeons to evaluate multiple different approaches to vascular visualization, testing clinically relevant tasks.
3. Discuss the clinical viability of these visualization approaches, taking into account the study results and surgeons' feedback.

1.3 Contribution

In the work of *Preim and Oeltze* (2008), providing an overview of vascular visualizations, they conclude that vessel visualizations need to be analyzed in depth with respect to clinical problems. Similar statements can be found in the literature throughout the years. *Preim et al.* (2016, 2018) state that if the goal of visualization is to improve clinical decision-making, more studies focusing on clinical tasks are required. They write that visualization surveys often rely on simplified tasks and computer science students, but in order to ensure that medical visualization techniques really are useful in a clinical setting, there needs to be more surveys featuring medical professionals performing relevant clinical tasks.

In this thesis, I investigate the suitability of several vascular visualization methods with respect to pre-operative planning, by performing a user study with surgeons to determine their confidence, accuracy and ease of use. In addition, I will discuss the work required to produce the visualizations and their viability in a clinical setting. In the process, I also implement several visualization techniques from the literature, which is freely available for non-commercial purposes under the License Zero "Prosperity Public License", which can be found at https://github.com/stisol/ivrigst .

1.4 Thesis outline

In Chapter 2, I briefly cover some related medical background, and more thoroughly the related fields within visualization. In Chapter 3, I discuss some of the pre-existing work in these fields related to this thesis. In Chapter 4, I detail the visualizations I used or considered for use in this thesis, while in Chapter 5, I describe the implementation of my own vessel visualization tool. In Chapter 6, I cover the user study methodology, execution and responses. In Chapter 7, I discuss the results of the study and my own visualization tool. Finally, I conclude the thesis in Chapter 8, and suggest avenues for future work. Appendix A contains documents as printed and used in the user study.

Chapter 2

Background

This chapter provides background knowledge and some context for this thesis. In Section 2.1, I briefly provide some medical background on the vascular system being visualized. In Section 2.2, I discuss the visualization methods that are used in this thesis.

2.1 Medical background

When first working with medical volume data, it is easy to default to orienting the data or visualization so that the subject's head is pointing upward, and then refer to features as being "above" or "below" each other. However, surgeons will usually operate with patients lying down, making such terms potentially misleading. In a medical context, there are more precise anatomy terms used to describe these topological relations, known as anatomicomedical terminology (*Moore and Agur*, 2007, p.3). Some knowledge of these terms is necessary both to communicate clearly and to understand the names of some vessels, listed in Table 2.1.

In this study I will be focusing on the mesentery, which is the most relevant area to the colorectal surgeries my collaborating surgeons are performing. The mesenteric vessels are located in the gut, see Figure 2.1 for some surrounding con-

Term	Meaning
Superior or Cranial	Nearer the head
Inferior or Caudal	Nearer the feet
Anterior or Ventral	Nearer the front
Posterior or Dorsal	Nearer the back
Median plane	The centered vertical plane dividing the body into a left and right half
Medial	Nearer the median plane
Lateral	Further away from the median plane

Table 2.1: Medical terms describing spatial relations, adapted from (Moore and Agur, 2007, p.4)

Figure 2.1: Labelled drawing of the human circulatory system, cropped to the stomach. This thesis focuses on the superior mesenteric artery and vein. Drawn by Villarreal (2009) and released into public domain.

text. Briefly, the jejunum and ileum are the last two sections of the small intestine that connects to the large intestine. The mesentery is a wall of transparent membranes known as peritoneum, containing blood vessels, nerves, and more. The mesentery attaches the jejunum and ileum to the posterior abdominal wall.

When talking about blood vessels, we usually divide these into two categories. Oxygenated blood is pumped from the lungs to the rest of the body through arteries. Deoxygenated blood then flows back to the lungs to pick up oxygen again through the veins.

The first set of blood vessels we are interested are the superior mesenteric artery and its branches (see Figure 2.2), which runs in the root of the mesentery. From this we see the middle- and right colic arteries feeding the colon, as well as the ileocolic arteries feeding the ileum (*Moore and Agur* (2007)). Complicating matters, the right colic artery may not be present depending on how one defines it and where one looks for it (*Nesgaard et al.* (2015)). The second set of blood vessels we are interested in is the superior mesenteric vein and its branches. It runs mostly parallel to the superior mesenteric artery and splits into a middle- and right colic vein and an ileocolic vein.

At Haukeland University Hospital, pre-operative visualization of the mesenteric vessel tree to identify and map out the vascular variations is not part of the standard clinical routine for colorectal pancreatic cancer surgery. Surgeons found that attempting to interpret the CT data from slice views alone was very error-prone, and estimated a fifty percent error rate from what they thought was the case from the slice views to what they would later see during surgery. To remedy this, some surgeons would send the CT data to experts abroad, receiving a detailed report about the topology as well as some low-resolution images of the rendered vascular tree. While they reported that this helped with surgery preparation, the price for each visualization was several hours of work, and they were

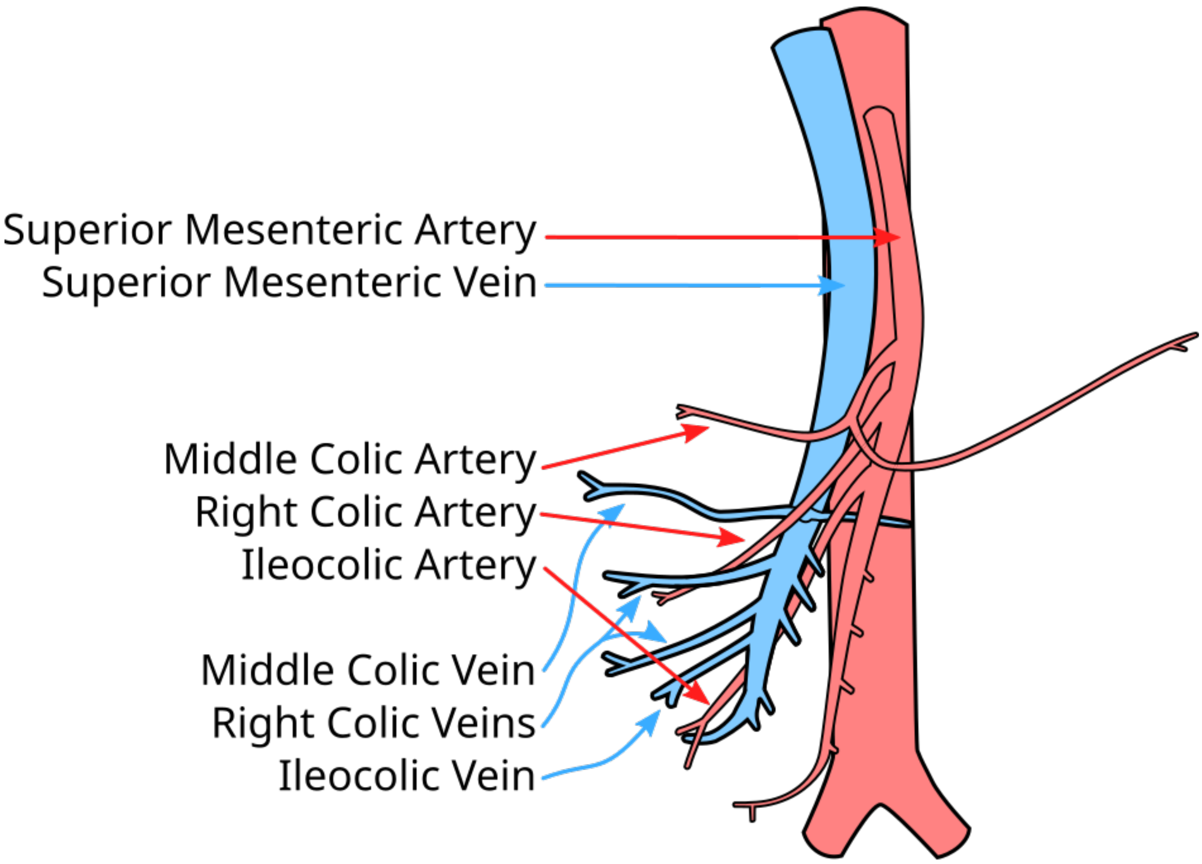


Figure 2.2: Labelled drawing of the superior mesenteric artery and vein. Adapted from the work of (Moore and Agur, 2007, p.144)

concerned about the sustainability of this process. This leads us to another requirement of vascular visualization for pre-operative use: it should not require a large amount of manual labour or visualization expertise to produce these images or reports in a timely manner.

2.2 Vascular visualization background

Vascular visualization is most commonly done using contrast-enhanced CT scan data. These scans provide volume data in the form of a 3D field of values. These numbers can be interpreted on the Hounsfield scale (*DenOtter and Schubert* (2021)), where the Hounsfield Unit (HU) of 0 is the x-ray beam absorption of water, and -1000 is that of air. When a contrast agent is introduced to the blood stream, blood vessel values range from around 100 to 600. By looking at this window of values, we can see the structure of the blood vessels with most other data hidden. However, even with a good window there will still be overlap with surrounding soft tissue, particularly other internal organs. This scale is also not entirely consistent between CT machines, patients, or scans, and the distribution of contrast agent and the timing of the scan with regards to the time of injection of the agent. All of these can change at what HU tissues can appear at. As we are warned by (*Preim and Oeltze*, 2008, p39) and others, this means that moving a chosen window by only one or two HU can lead to a different diagnosis entirely. For example, moving a transfer function up one or two HU can hide a bit of a blood vessel from the resulting image, making it appear to have a blockage or collapse. As such, careful manual adjustment to what ranges of values to include is practically always required to avoid misleading visualizations.

With this data, there are several visualization options. With direct volume rendering methods, we usually render the volume directly by casting rays through the volume. First, we define a transfer function that takes a value from the volume as input, and provides the opacity and colour of said value as an output. With this in place, we can render using a technique known as raymarching. This works by stepping through the volume along a ray for each pixel to render, accumulating the color and opacity of each point the as it progresses to determine the final color for a given pixel on the screen.

Direct volume rendering has several distinct advantages. For one, it does not require any laborious segmentation work that could introduce errors. They also retain the surrounding structure and organs, giving context clues that can be helpful to retain spatial awareness. However, they are not without drawbacks. Transfer functions are difficult to set up without experience and do not trivially adapt to new datasets. This can be mitigated by designing a good transfer function and then allowing the user to make small adjustments to it, as they can often be re-used by correctly translating and scaling the function to fit the new data.

The other category of visualization methods is indirect volume rendering. Here, we use the volume data to create a mesh of the blood vessel through a segmentation process. With this mesh, traditional surface rendering techniques can be used to display the model. This makes it easy to use existing techniques such as hatching, depth shading, shadows and coloring to make the vessel topology easier to read.

With a segmented surface mesh, we can use traditional shading and reflectance models for illumination. The Blinn-Phong reflectance model (*Blinn* (1977)) is an industry default for calculating ambient- and diffuse lighting with specular highlights. The reflectance model by *Oren and Nayar* (1995) for diffuse surfaces can improve the lighting further for rough surfaces, and *Cook and Torrance* (1982) presents an alternative model for specular highlights. An alternative approach is to use cartoon-inspired "toon" shading to emphasize shapes. It is unclear if any particular method is superior to the others — in a study by *Ostendorf et al.* (2021), they found that there was significant disagreement between experts about which of these are preferable for vascular visualization.

Segmentation methods can be roughly divided into three categories. Manual segmentation refers to when a user manually "paints" what parts of the volume belong to the segmentation. Automatic segmentation is when an algorithm does all the work, although no such algorithm has reliably segmented mesenteric vessel trees yet to my knowledge. Semi-automatic methods cover hybrid solutions, such as the user placing seed points at the start and ends of a vascular tree and letting an algorithm fill in between them.

While the resulting image of a cleanly segmented vascular tree can be clearer for the viewer (see Figure 4.1 and 4.2), the segmentation process can introduce errors. As indirect volume rendering requires a consistent mesh, any ambiguities in the data need to be resolved or decided by the person or algorithm doing the segmentation work. Branches can be missed or connected to vessels they are not in reality, while in a volume rendering context that uncertainty is visibly ambiguous. The segmentation process can be very laborious when done manually, often taking hours to produce, and automated vessel segmentation remains an open problem (*Rudyanto et al.* (2014)).

It is currently faster to adapt a transfer function to direct volume rendering for new datasets than to manually segment a volume for indirect volume rendering. Manual segmentation is slow and laborious, taking hours to produce, but the images are uncluttered and easy to interpret. Thus I would like to see if the advantages of indirect volume rendering can make up for the extra work required, either now or perhaps when automated segmentation algorithms and segmentation tools continue to improve. It might also be that volume rendering with a sufficiently well-made transfer function is just as good, and that the extra segmentation work to is not necessary to get reliable visualizations.

Chapter 3

Related Work

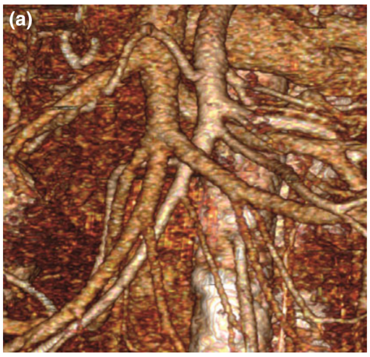
In this chapter, I discuss related work in the field that this thesis builds upon. First, in Section 3.1, I go through some articles about mesenteric surgery and the impact of visualization from a medical perspective. Then in Section 3.2, I go through related visualization work for both indirect- and direct volume rendering. For indirect volume rendering, this also covers related segmentation methods.

3.1 Mesenteric surgery

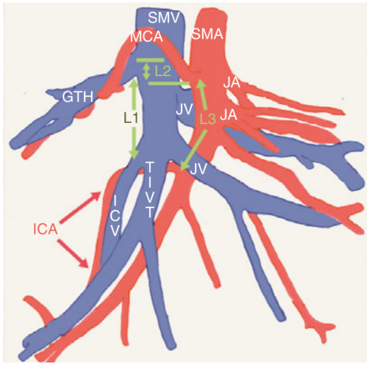
In a paper describing a method of resectioning pancreatic head cancers, *Katz et al.* (2008) conclude that knowing the mesenteric vascular anatomy in advance is vital to ensure consistently successful surgical procedures in the area. *Spasojevic et al.* (2011) demonstrate that CT scan data can be used to to display the topology of the mesenteric vessel anatomy in patients, and *Natsume et al.* (2011) find that pre-operatively classifying anatomical variations in these vessels help reduce bleeding during pancreatic cancer surgery.

For colorectal surgery, *Nesgaard et al.* (2015) compare similar volume visualizations CT volume data with findings from the surgery of the same patients to determine their accuracy — see Figure 3.1 for an example of this process. They find that CT-reconstructed anatomy is reliable and accurate. Of the 139 patients participating in the study, they only had three false-negative and one false-positive finding, and the three former findings were all from low-resolution CT scans. *Coffey* (2015) comments on their findings and states that pre-operative appraisal of the vasculature is becoming increasingly important to do.

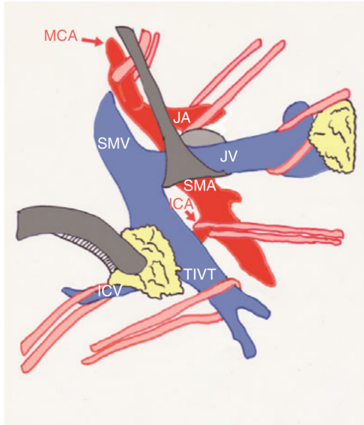
In a follow-up paper, *Nesgaard et al.* (2017) finds that 8.2% of the 340 patients they reviewed had arterial abnormalities which would be hazardous if inadvertent injury occurred during surgery, and that these abnormalities could reliably be found during pre-operative scanning and visualization of the vessel tree, providing surgeons the opportunity to prepare for this. In yet another follow-up paper, *Stimec and Ignjatovic* (2020) continue studying variations in the ileocolic



(a) Pre-operative DVR Osirix reconstruction.



(b) Schematic outline based on reconstruction.



(c) Schematic outline based on surgery photographs.

Figure 3.1: Volume visualization of the midgut mesentery based on CT data rendered with Osirix. Illustration by Nesgaard et al. (2015), Copyright © 2015 John Wiley and Sons

vessels, concluding that pre-operative visualization is a powerful tool and neglecting to use it could have "dire consequences" for colon surgeries.

These studies highlight the need for a good understanding of vascular anatomical variations to mitigate risks of bleeding during surgery, improving their outcome.

3.2 Visualization

As discussed in Chapter 2.2, there are two broad categories of volume visualization. With indirect volume rendering, we produce a segmented mesh to render with traditional rendering techniques. As such, Section 3.2.1 about indirect volume rendering will also focus on this segmentation process. Similarly, Section 3.2.2 about direct volume rendering will also focus on transfer functions, the quality of which is critical to achieve a good visualization.

The work in this thesis builds upon the work by *Smit et al.* (2016), visualizing anatomical variation in blood vessels. VarVis was developed as a vessel topology variation teaching tool and as such could afford significant manual pre-processing, while this work aims to evaluate visualization techniques for patient-specific data in a clinical setting.

3.2.1 Indirect volume rendering

In indirect volume rendering, the volume of interest is segmented into a surface mesh which can then be visualized using conventional means. *Kersten-Oertel et al.* (2014) have evaluated a variety of visual cues and channels for their impact on depth perception in surface rendering for blood vessels. They found that the two most effective channels were chroma depth and aerial perspective (effectively encoding depth information on the hue and saturation channels), which we make

Figure 3.2: Surface rendering of the portal vein of the liver, using hatching to express shape and depth relations. The color differentiates sub-trees supplying different areas of the liver. Illustration by Ritter et al. (2006), Copyright © 2006 IEEE

use of in this work. *Ritter et al.* (2006) provide a GPU hatching texture method to make spatial relations between vessels easier to understand at a glance. The method is similar to a halo effect, but also provides enhanced shape perception by drawing hatching lines following the shape of the mesh. Of particular interest to this thesis, it also highlights vessels passing over each other with a shadow-like hatching around the occluding vessel that is projected onto the vessel underneath, a method I have made use of in my rendering program.

Another way to provide depth perception to the user is by providing three-dimensional images. *Heinrich et al.* (2021) find that depth estimations are more accurate and confident using virtual reality setups than when viewing that data on a traditional monitor. While this is very promising, this would require dedicated hardware and a virtual reality workstation at the hospital where the user study is performed. Due to these difficulties, I have not explored this direction further in this thesis.

There is a variety of different segmentation methods for use with volume data. Manual segmentation is quite laborious and takes hours to finish, while automated or semi-automated methods can make mistakes that are harder to spot. In the work by *Boskamp et al.* (2005), they suggest a number of techniques and algorithms for analysing or segmenting volume data. Removing bones and organs and running vesselness filters to enhance tubular structures as part of a pre-processing step can greatly enhance the quality of segmentation tools used later in the process. Further, noise and artifact filters can be used to connect disjoint vessels, fine-tune branching points, smooth results and remove noise during post-processing. After the segmentation process is complete, they also suggest a skeletonization process can be performed to get centerline data for further analysis on the vessel structure, which is beyond the scope of this project.

In the work by *Lesage et al.* (2009), they review a wide range of segmentation techniques and algorithms to partially automate the segmentation process process. However, when *Luzon et al.* (2020) performed a qualitative comparison of manually segmented mesenteric vascular models and models produced using semi-automated methods, they found that the latter could cause "considerable confusion" during surgery. Anecdotally, I experienced similar issues while segmenting vessels for this study. Semi-automated tools can frequently "spill over" segmentation into surrounding tissue or organs, reducing my own confidence in the segmentation and leading to additional work cleaning up the model afterwards. It may be that these methods are better suited to vessels with more contrast against their surrounding, such as vessels in the lungs. As such, I did not end up using these segmentation methods.

Going beyond semi-automated methods, fully-automated segmentation algorithms usually focus on vasculature in the lungs, eyes or brain. The work of *Thamm et al.* (2020) provides a very promising automated segmentation of cerebral vasculature with a goal of detecting occlusion candidates in stroke cases. The VESSEL12 study by *Rudyanto et al.* (2014) compared fully automated vessel segmentation algorithms on CT scans of the lung. The submitted approaches have various pre- and post-processing steps, and fall into one of four categories: region growing, thresholding, machine learning, and variants and implementations of Hessian-based vesselness filters. Later, *Moccia et al.* (2018) provided an excellent overview of the state of the art in automatic vessel segmentation. They make some important observations:

- No single automated segmentation technique performs well across all contexts, such as image quality, noise levels, illumination, or different regions of the body.
- Not much research has been done on adapting these methods to also segment pathological vessels.
- Deep learning methods are promising, but are being held back by the lack of a sufficiently large and diverse collection of validated medical datasets to train on, spanning the variability of vessel anatomy and also recognizing potentially pathological tissue.

As I found automated- and semi-automated segmentation algorithms to not yet be mature enough for segmenting mesenteric vessels, I ultimately decided to commit to manual segmentation to prepare meshes for indirect volume rendering in this thesis.

Because the segmentation process can introduce errors or inaccuracies, there is ongoing research into visualizing uncertainty in segmented data. In the work by *Ristovski et al.* (2017), they suggest several methods. One of these is to display data uncertainty on the surface of the segmented model by coloring the surface of the mesh. By highlighting areas where the segmented data can not be relied upon to be accurate, this may improve confidence in the parts of the segmented data where the error margins are smaller. While promising, the time and effort it would take to implement this has resulted in it being out of scope for the visualizations used in this thesis, but uncertainty visualization will be brought up again in Chapter 8.

3.2.2 Direct volume rendering

Direct volume rendering is a technique where a volume of values is rendered without an intermediate step to create surface representations of parts of it, a technique which was first used for medical CT data (*Drebin et al.* (1988); *Hohne and Bernstein* (1986)). A common way to do this is raymarching; for each pixel on the screen, a “ray” is cast from the camera. This ray marches in steps through the volume, adding colors and opacity from the material as it traverses it until the summed up color is fully opaque, and then the color is rendered to the screen. There are many ways to further improve the result, such as adding more advanced lighting techniques (*Ament and Dachsbacher* (2016)) or highlighting features of interest through halos (*Díaz et al.* (2010)) or by peeling back obscuring features (*Bruckner et al.* (2006)).

With all these methods, each value in the volume needs to be assigned some material properties to distinguish them. The function that maps these values to properties is called the transfer function, and in it’s most basic form it maps the value of each point in the field to a color and opacity. There are also more advanced transfer functions, such as ones that provide additional material properties (*Bruckner et al.* (2006)), or two-dimensional transfer functions that take both the value and the derived gradient vector of the volume values as input (*Ljung et al.*, 2016, p.682). The gradient vector lets the transfer function take some local context into consideration, allowing it to further emphasize features such as vessel walls or other organ boundaries characterized by a large change in value in the data. Methods such as these make it possible to more distinctly map material properties to features such a bones, vessels or organs, but take more experience and work to create.

Transfer functions are unfortunately a source of potentially misleading visualizations. Small changes in the transfer function can result in significant changes in vessel width, making healthy vessels look pathological or vice versa (*Persson et al.* (2004)). *Lundström et al.* (2007) suggest visualizing this uncertainty through animation, by animating the transfer function and moving the window to include slightly lower and higher values. This shows a wider range of interpretations of the data, to counteract the possibility that picking a specific transfer function may introduce some errors while resolving others. This is less critical in my thesis, as we are interested in the vascular topology more so than the shape or pathology of individual vessels.

A specialized approach for vessels is proposed in VesselGlyph (*Straka et al.* (2004)), which uses the extracted centerline of the vessel tree as part of the transfer function to determine opacity in a direct volume rendering. This lets the vi-

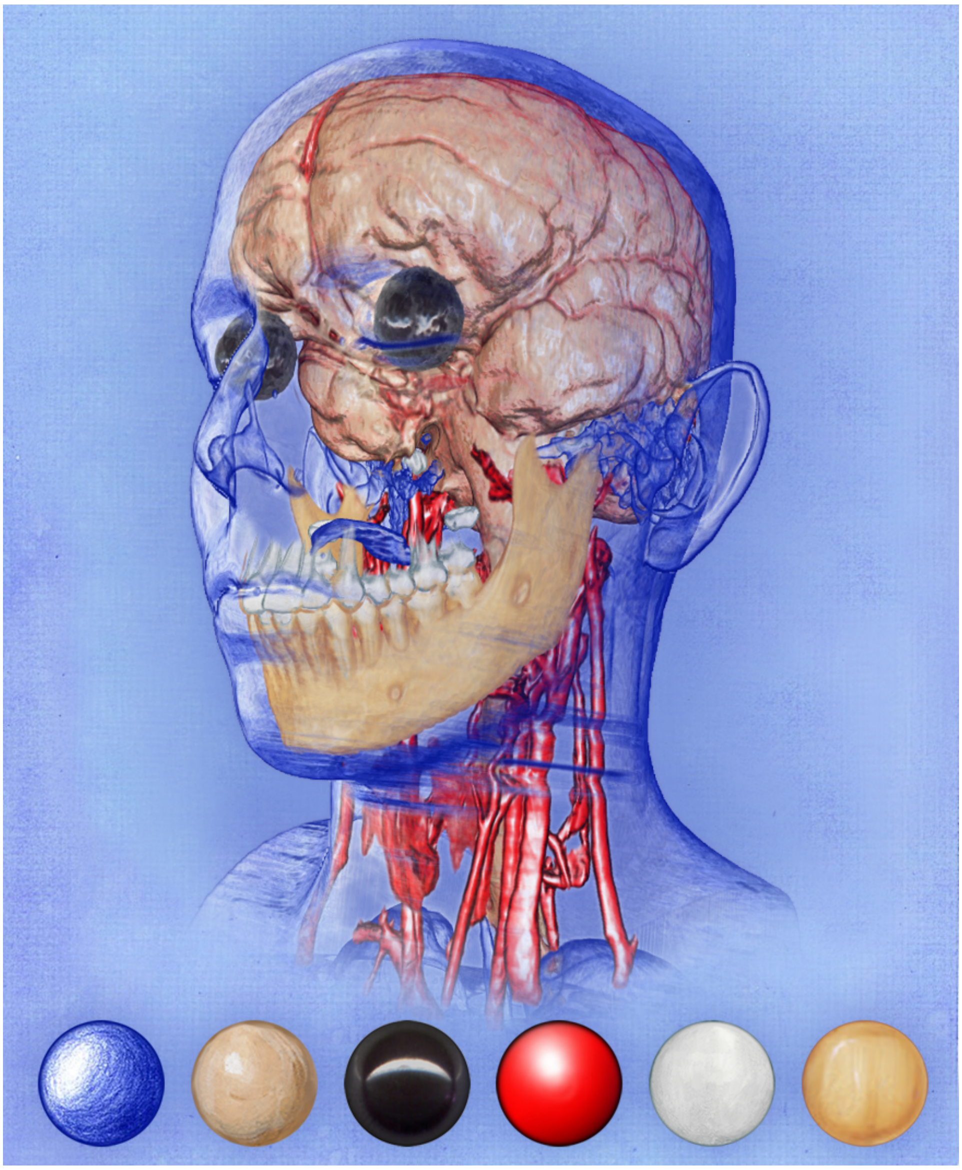


Figure 3.3: Direct volume rendering of segmented volume data using a style transfer function based on data value and object membership. Illustration by Bruckner and Gröller (2007), Copyright © 2007 John Wiley and Sons

sualization retain the context of surrounding structure in the visualization, while also using the knowledge of where the vessels are to highlight the vessels or even hide any occluding tissue. Due to the significant workload required for centerline extraction, I did not attempt this for this study.

In the work by *Joshi et al.* (2008), they describe the use of polar coordinates to determine vesselness in volume data, and suggests a number of visualization techniques to enhance volume-rendered images. These include visualizing depth or shadows with colder (blue-tinted) colors, as well as surrounding halos to easier see delineations between structures. While I do not make use of polar-coordinate vesselness filters, their use of blue-tinted shadows and alternate shading techniques did inspire me to use similar techniques in my indirect volume rendering tool.

One issue with CT data with regards to volume rendering of vasculature is that sometimes the features of interest are spread amongst multiple volumes. This is a result of how CT angiography scans are conducted; a contrast agent is usually injected into a vein, making them stand out against surrounding tissue in the CT data (*Silverman et al.* (1984)). It is common for this method to produce one volume dataset for the arteries (where veins are barely visible), and one for the veins (where the arteries are less visible). This happens because by the time the contrast agent has spread to the veins, it is diluted and less present in the arteries. As the scans are taken with a bit of time separating them in order to catch both of these two states, the vessel positions in the scans can be offset with relation to one another as well due to patient movement and breathing. This means that in order to see both arteries and veins, it may be necessary to translate and rotate one volume to more closely overlap with the other, and then to mix the two datasets with appropriately adjusted transfer functions to see the full vascular system (*Cai and Sakas* (1999); *Lawonn et al.* (2018)).

Chapter 4

Visualizations

In this chapter, I outline some of the visualization techniques I have evaluated for use in this thesis based on existing literature regarding vascular visualization, including those implemented in the tool I have made for this purpose. There is a lack of ready-to-use visualization tools implementing advanced vessel visualization techniques, which means that time that would be required to implement them from scratch is substantial. Therefore, to limit the scope of the thesis, not all methods could be included.

4.1 Direct Volume Rendering

There are many tools available that can do direct volume visualization. Some, like MeVisLab, are very flexible but may require a high level of familiarity with the tool to assemble a high-quality visualization. I use 3D Slicer (*Pieper et al.* (2004), Figure 4.1) as my direct volume visualization tool for this survey as it provides excellent transfer function presets that were easily adjusted to fit new datasets.

The downside of using a third party renderer is that some advanced volume rendering techniques may not be implemented in the chosen tool. In this case, 3D Slicer does not support chroma depth, aerial perspective shading or shadows. While these features would be useful and can potentially be beneficial to the clarity of the visualization, they have been left out in a concession to practicality. Exploring the full range of methods available would inflate the parameter space of visualizations to implement and evaluate in the study beyond what is feasible.

4.2 Indirect Volume Rendering

In a survey by *Preim et al.* (2016), they highlight chroma depth and hatching textures as effective means to provide depth perception to the user. Chroma depth techniques colors the surface based on distance from camera, while hatching techniques highlight cases when a structure is in front of another to make the depth

Figure 4.1: Direct volume visualization using 3D Slicer.

relation clear. Other techniques from the survey include toon/tone shading to enhance shape perception through less realistic, more exaggerated lighting.

As there is a lack of openly available tools that implement advanced surface shading algorithms for vessels, I developed an application for rendering segmented vessel meshes (see Figure 4.2) and for experimenting with rendering techniques. The implementation details for this can be found in Chapter 5. With the results from above in mind, the tool I developed supports blending between the Blinn-Phong-based shading and a more stylized toon shading to distinctly visualize the shape of mesh surface. Depth perception is provided through distance shading on the hue, saturation, or value channels, and can be further highlighted with hatching textures to highlight depth relations between structures. Inspired by *Stoppel et al.* (2019), it has a controllable dynamic light source that casts shadows, which can move in gentle circles to provide some shadow movement.

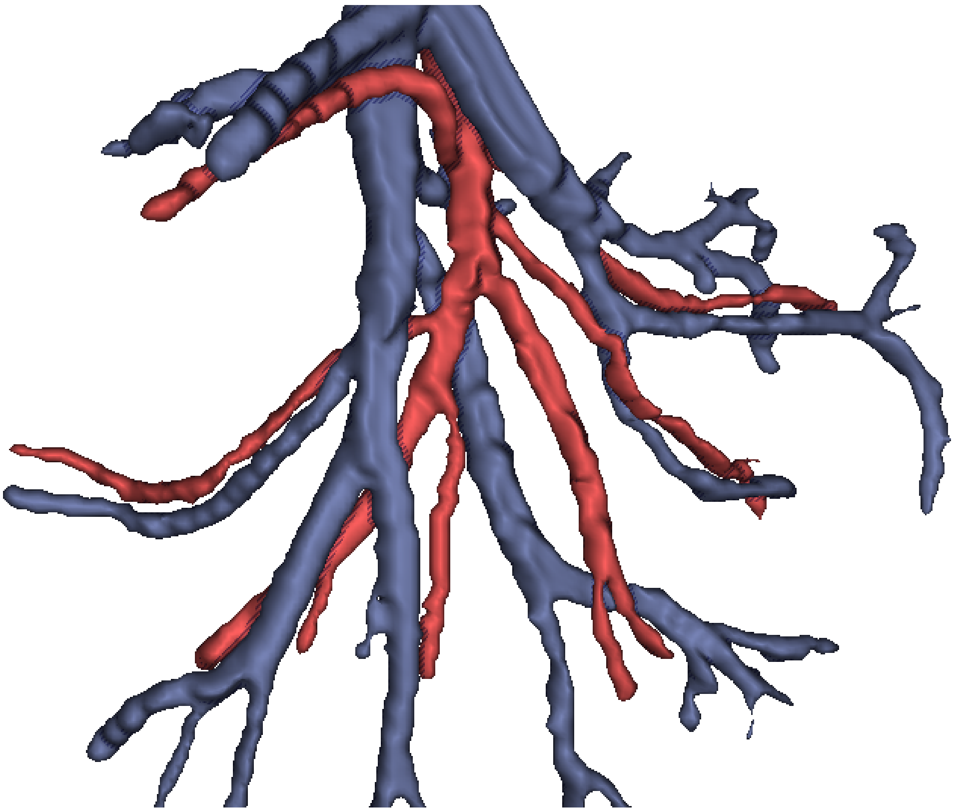


Figure 4.2: Own renderer displaying segmented model. Arteries are colored red and veins are colored blue by convention.

Chapter 5

IVRIGST — My Indirect Volume Rendering Tool

In the process of finding suitable visualizations for these evaluations, I did not find a surface visualization tool with all the features I wanted. In addition, some features like hatching and shadows require multiple render passes, meaning visualization frameworks that allow you to modify just the fragment shader would be too inflexible for my use. As such, I wrote my own tool for this. The "Indirect Volume Rendering and Interactive General-purpose Shader Tool" (IVRIGST) has a user interface for changing visualization settings on the fly as well as the ability to hot-reload shaders, significantly reducing development time. The resulting software is relatively small — including the shader programs it consists of roughly 3000 lines of code. The source code for the application and the shader programs used are freely available for non-commercial use under the License Zero "Prosperity Public License" at `https://github.com/stisol/ivrigst` .

5.1 Tools, languages, and libraries

To get started quickly, I decided to use the Rust programming language for my application as I am familiar and comfortable it, and it's compatibility with C means that OpenGL learning resources intended for C or C++ are still usable. OpenGL was chosen as it is significantly easier to work, a lot less verbose than graphics APIs like Vulkan, and works well on all modern computers. Likewise, I chose `SDL2` for window creation as it is a well-known and widely used windowing library that works well on all modern operating systems.

The abstractions I used to work with OpenGL are adapted from *Arlauskas* (2018), and my implementation of shadows and render targets are adapted from *"Calvin1602"* (2011).

I chose `egui` to create a small user interface, as it is fairly straightforward to integrate with a custom rendering stack. Being an immediate-mode user interface (UI) library, it is called each frame with the UI elements wanted in the order they are to be rendered within the modal windows. State is managed by passing

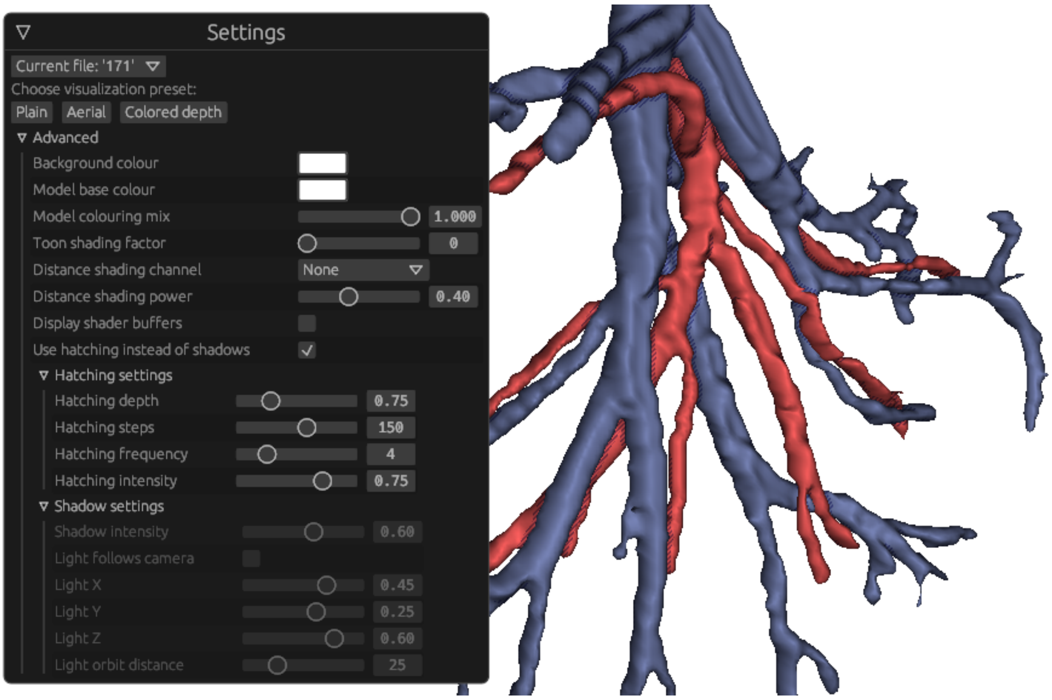


Figure 5.1: The user interface for the IVRIGST, made using `egui`.

a variable for each interactive element as well as the user mouse and keyboard input, and the library changes the given variables according to user interaction. Finally it produces a list of vertices to render along with it's own texture, the result of which can be seen in Figure 5.1.

Linear algebra is key to 3D rendering, and for this I use the `nalgebra` library to assist with matrix operations, building perspective transformation matrices, and other matrix operations.

Library	Short description
`gl`	OpenGL bindings.
`sdl2`	SDL2 bindings and library for opening a window.
`nalgebra`	Linear algebra library.
`egui`	Small UI library inspired by Dear ImGui.
`tobj`	Wavefront OBJ file loader.
`notify`	Cross-platform file watching library used to hot-reload shaders.
`clipboard`	Cross-platform clipboard library.
`webbrowser`	Cross-platform used to open links.
`walkdir`	Directory traversing library used in build script.

Table 5.1: A list of dependencies used.

5.2 Implementation

In this section I will discuss the implementation of IVRIGST. The first subsection will describe the core rendering loop. The rest of the section will detail the implementation of individual rendering techniques.

5.2.1 Setup and core rendering loop

At application startup, the SDL2 windowing library is initialized to open a window and create an OpenGL context. A given blood vessel mesh is then loaded into memory and the shader programs are compiled. The camera is initialized and then the main loop is entered. Window events from SDL2 are processed to handle window resizing, user input, closing the application, and so on. User mouse and keyboard input is used to move the camera, as well as forwarded to `egui` for UI interaction.

Model loading is handled through `tobj`, a “Tiny OBJ Loader”, as it provided an easy to use API for loading standard Wavefront object files. While it loaded vertex positions and normals as expected, the library did not initially support per-vertex inline colors. This turned out to not be too time-consuming to add this myself, and so version 3.1.0 of the library includes my contribution [1] adding this feature.

The first render passes are done by the model renderer. It does a pass for shadows, another for hatching, and then a main render pass to display the model. Next, the user interface is rendered by taking `egui`’s texture and vertex data and rendering it on top of the model. Finally, if the renderer debugging option is selected, two additional passes are done to display the shadow and hatching texture buffers on-screen for development purposes. If any shader files have been updated since the last run of the main loop, they are recompiled and re-initialized to be used for the next frame.

This straightforward architecture allowed for the rapid development of new visualization options, by either editing shader files on the fly or by inserting additional rendering passes into the process. The way the main model shader works also made it easy to add additional UI elements to change shader uniforms on the fly by simply adding a handful of lines of code.

5.2.2 Toon shading

Toon shading is a simple way to enhance shape perception and adding contour lines to the vessel. This is an alternative to Blinn-Phong shading, where instead of attempting to emulate “realistic” lighting, it quantizes the shading into steps. To dampen this effect slightly while retaining some of it’s characteristic features, I blend the colors produced by both shading methods (see Figure5.2).

Ultimately this was deemed to be a bit distracting and unfamiliar in pilot surveys and were removed from the presets. Instead, I modified the Blinn-Phong shading by adding diffuse lighting calculations by *Oren and Nayar* (1995) and specular lighting calculations inspired by *Cook and Torrance* (1982).

[1] https://github.com/Twinklebear/tobj/pull/44

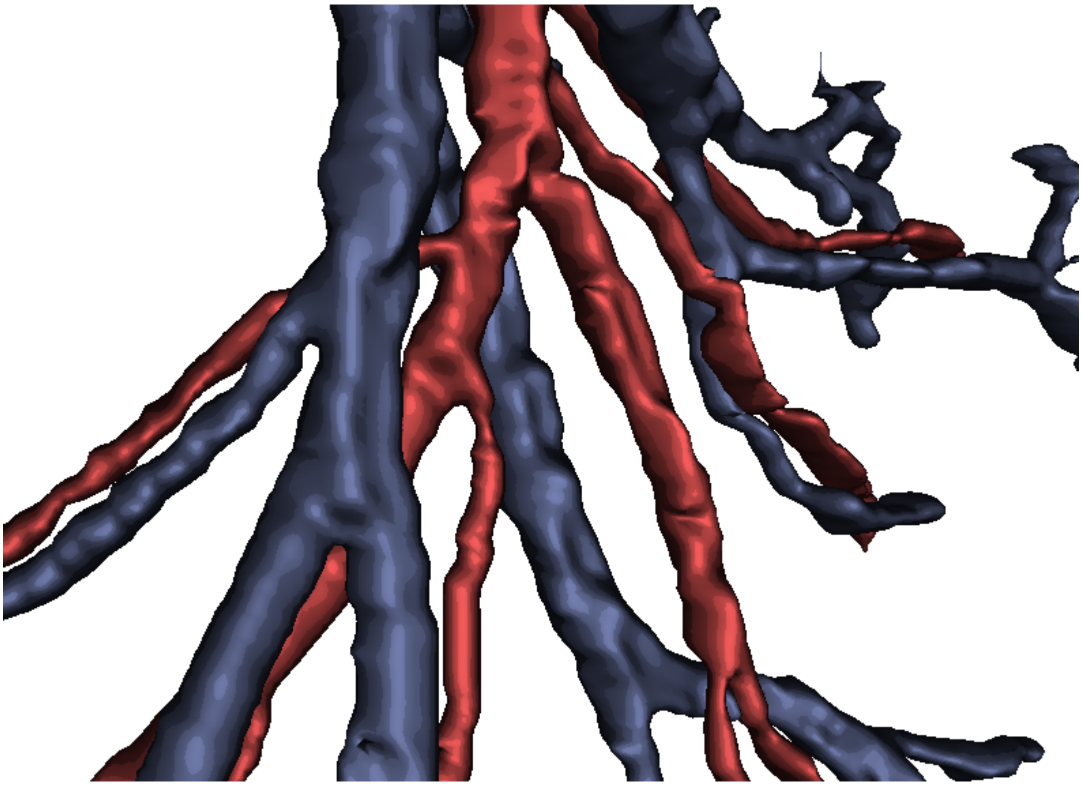
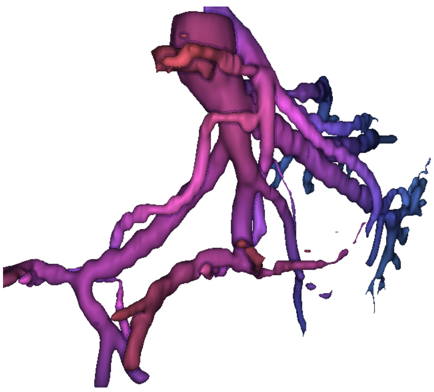


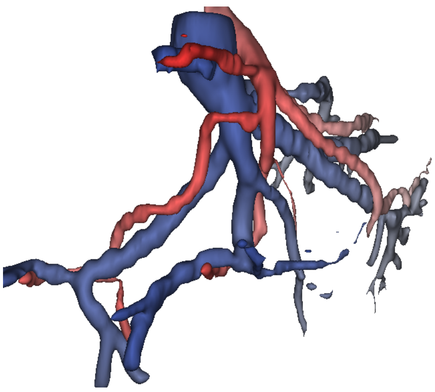
Figure 5.2: Vessel tree with toon shading mixed in.

5.2.3 Distance shading

The goal of distance shading is to enhance depth perception by using another visualization channel to add depth cues. These methods are generally simple to implement and convey depth very effectively (*Kersten-Oertel et al.* (2014)). IVRIGST supports depth shading through hue (pseudo-chroma depth, see Figure 5.3a), saturation (aerial view, see Figure 5.3b) or value (darkness at distance). This is done by converting the final color of the pixels from RGB to HSV, changing the selected color channel based on its depth in the image, and converting it back to RGB for rendering.



(a) Depth shading on the hue channel — "pseudo-chroma depth".



(b) Depth shading on the saturation channel — "aerial view".

Figure 5.3: Vessel tree with distance shading using the hue and saturation colour channels.

5.2.4 Shadows

Shadows are a natural feature of light that can help provide a sense of depth and distance. This is implemented by rendering the scene from the perspective of the light source, storing depth information in a texture. The main rendering step can then see if the pixels rendered are "behind" what the light source saw when transformed into its coordinate space. If so, it is in shadow, and can be made darker or tinted blue (*Šoltészová et al.* (2011)) to show this.

Inspired by *Stoppel et al.* (2019), the light source can additionally be set to move in gentle circles in order to keep the shadows from being entirely static. While the idea was that this would further make it easier to get an impression of what features are casting shadows, pilot studies indicated that the shadows mostly just got in the way. At worst, the effect caused a distracting illusion of movement. As such, they are not present in the final user study.

5.2.5 Hatching

I use hatching as an alternative to shadows to highlight depth relations specifically, making it clearer what vessels are in front of or behind the others. Inspired by *Ritter et al.* (2006), the scene is rendered from the camera's perspective, saving the depth information. During this process, all vessels are enlarged by adding the vertices' normals to their position. Similar to shadows, this means the main render step can compare fragment depth information with that of the hatching texture to find out if it is obscured by the enlarged vessel. This creates a "halo"-like shadow effect around vessels, projected onto vessels behind them (see Figure 5.4). A small triangle function turns this shadow into a simple diagonal hatching texture to make the effect more subtle and to avoid significant distortion of color.

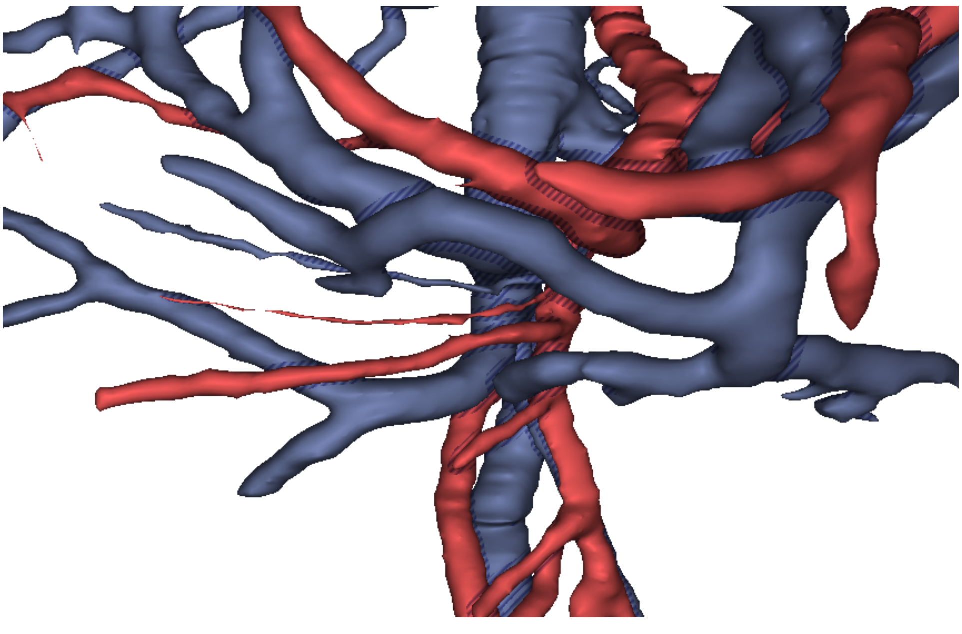


Figure 5.4: Vessel tree rendered with an exaggerated hatching effect.

Chapter 6

Evaluation

According to *Preim et al.* (2018), many medical visualization studies are too low level, focusing entirely on perception-based evaluation. In such studies, the tasks that are measured are not directly related to diagnostics or treatment decisions. They are frequently over-simplified, studying static visualizations and screenshots of what would be interactive 3D visualizations when applied in a clinical tool. The advantage of this approach is that there is no medical expertise required to measure the reliability of depth perception techniques, and as such, survey subjects are more easily found and sample sizes can be a lot larger.

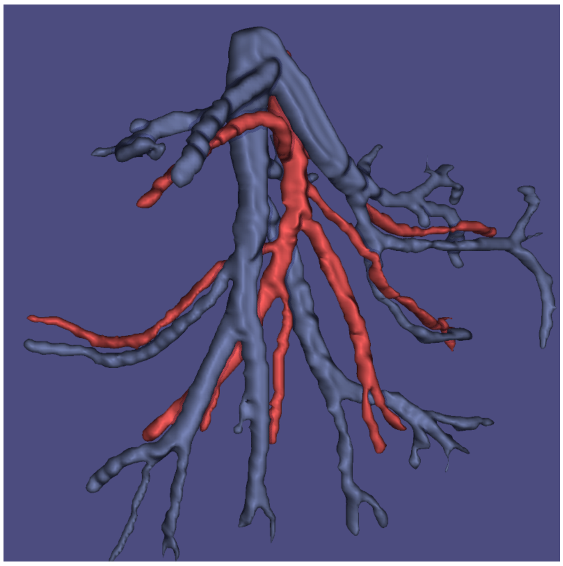
Tools like EvalViz by *Meuschke et al.* (2019) can make visualization surveys a lot easier to execute. EvalViz takes models, points and shader files as input, and generates easily administered surveys in a website format that ask users to answer questions related to depth or shape perception. While undoubtedly useful, this tool does not support volume data, a requirement for direct volume rendering, and as such could unfortunately not be used for this study. Instead, I use 3D Slicer, IVRIGST, and a printed list of tasks and questions for this study.

6.1 Evaluation setup

This study is built using the guidelines for task comparison surveys from *Smit and Lawonn* (2016), as well as advice by (*Kitchenham and Pfleeger*, 2008, p. 63-92) regarding common evaluation pitfalls.

The data used in this study was anonymized and approved for research purposes. I received access to three series of volume data in the DICOM data format. Two of the datasets were taken with lower precision (3mm), while the third was of higher quality (1mm). To avoid bias towards visualizations using the higher quality dataset, the two lower-quality sets were used for the tasks and questions, while the third and higher-quality dataset was used to give the participants some time to familiarize themselves with the software without yet seeing the vessels they would be completing tasks with. For these datasets, we received a third-party expert analysis answering several anatomical and topological questions, which we could check against the participants' answers to look for inconsistencies. The volumes

(a) Direct volume rendering using 3D Slicer.



(b) Indirect volume rendering using IVRIGST.

Figure 6.1: Screenshots of the direct- and indirect volume rendering tools used in this study, both displaying dataset #1.

for indirect volume rendering were manually segmented by me using 3D Slicer's segmentation module, and the resulting mesh was looked over by a surgeon and radiologist to check for any visible mistakes.

Each surgeon was presented with one of two variations of the study. Either they would receive the IVR visualization for dataset #1 and the DVR visualization for dataset #2, or the other way around. When I got the chance to interview a third surgeon, this caused an imbalance where one of those variations were used twice, while the other variation was only used once.

The tasks are performed in two visualization tools; 3D Slicer for DVR, and IVRIGST for IVR. Figure 6.1 contains screenshots of the two applications displaying dataset #1.

The participants were handed a printed document with these tasks to perform and questions to answer. Inspired by the survey by *Smit et al.* (2017), the opinion questions are found in Table 6.3, and the tasks in 6.1. While the opinion questions ask for subjective opinions and their confidence in the visualizations, the tasks are there to measure the accuracy of the visualizations by asking concrete questions about the topology of the vasculature. These questions were designed together with the surgeons involved, in order to make sure that the questions are useful with regard to preparing for the surgical tasks that they perform. The tasks also ask for the participant's confidence in their answer. The opinion survey consists of Likert-type questions (*Clason and Dormody* (1994)) asking the participant to rate their agreement with various statements about the visualizations on a five-point scale, known as Likert-type questions.

While our partner surgeons were also interested in measuring the distance between the ileocolic vein and the GTH (recall Figure 3.1b), we did not include this in our study due to software and time limitations. It is also arguably less of a visualization challenge and more of a software tooling challenge, although properly communicating the uncertainty given by having to decide at what values the vessel wall is positioned at can be an additional interesting research problem (*Lundström et al.* (2007); *Ristovski et al.* (2017)).

ID	Question	Answer			Confidence		
T1	Does the ileocolic artery pass anterior or posterior to the superior mesenteric vein?	Anterior	Posterior		Low	Med	High
T2	Is the middle colic artery cranial, caudal or on the same level as the GTH?	Cranial	Caudal	Same	Low	Med	High
T3	Is there a right colic vein present with confluence to the middle colic vein?	Y	N		Low	Med	High
T4	Is there a right colic artery present?	Y	N		Low	Med	High
T5	Does the right colic artery cross anterior or posterior to the superior mesenteric vein?	Anterior	Posterior		Low	Med	High
T6	Is an accessory middle colic artery present?	Y	N		Low	Med	High

Table 6.1: Tasks given for surgeons to complete using the visualization tools.

6.1.1 User study pilot

In order to find and resolve any issues with the user study before starting to interview surgeons, I piloted the study with a pair of fellow students. A particularly interesting bit of feedback was on the topic of pseudo-chroma depth. They noted that the way features of the vessel changed colors as the camera angle moved was disorienting, and actively prevented them from keeping track of vessel structures. It was also noted that this effect may be exaggerated by their unfamiliarity with vascular trees, but it is still an interesting observation on the drawbacks of dynamic depth coloring when applied to interactive visualizations. However, on a larger vessel tree with more vessels pointing in all three dimensions, they found it useful in keeping track of vessel structures moving in relation to one another, so perhaps some experience with the method is required to overcome the initial confusion. This would be interesting to investigate further, but is ultimately out of scope of this thesis.

Another comment I received was that the shadow effects did more harm than good. Static shadows were in the way and didn't provide a perceived benefit to the subjects, while the moving shadows were actively distracting and sometimes gave an illusion of motion that was not present. As such, this was cut from the provided visualization presets.

6.1.2 Administering the study

We had three participating surgeons for this study. Two of our participants are active surgeons at the Haukeland University Hospital. Surgeon #1 is a professor, and surgeon #2 is a PhD candidate. Surgeon #3 wished to remain anonymous. The participants were given a laptop with the visualization tools already running, and were free to manipulate the tools as desired. Each visualization tool was pre-loaded with a different dataset. For each participant, which tool showed what dataset was randomized in order to avoid a bias of an "easier" dataset. The order in which the visualizations were presented was also randomized.

After being introduced to the tools and allowed some time to familiarize themselves with their features, a new dataset was loaded into the chosen first tool and the subject was asked to answer six topology questions (see Table 6.1). Once done, they were asked another five general opinion questions about how they found the visualization, and another two specific to the visualization method. The complete evaluation form is available in Appendix A. Then this process was repeated on the other tool with a new dataset. At the end, they were asked for their subjective preference of the two.

6.2 Evaluation results

Table 6.3 contains all answers to the tasks and opinion survey for each dataset. Table 6.1 breaks down the opinion survey for each visualization method. The tables in this section are color coded using a colorblind-friendly palette generated using the excellent ColorBrewer tool by *Harrower and Brewer* (2003), available at https://colorbrewer2.org/. It is worth noting that two confidence answers were unfortunately missed at the time, and question T5 turned out to not be relevant for these datasets as it concerned a vessel that was not present.

While using the direct volume rendering tool, the surgeons generally reported lower confidence in their answers. Even so, all surgeons submitted the same answers with the exception of question T6. This question asks "Is an accessory middle colic artery present?", which is a difficult question as it can only be identified in relation to other arteries, which themselves are named with reference to the organs they supply. For both datasets, answers given with indirect volume rendering are high confidence, while direct volume rendering answers were given with lower confidence. Comparing the answers to our third party analysis, the answers given with DVR are correct for question T6, while the answers given with IVR are incorrect.

All three surgeons expressed a clear preference for the indirect rendering method and wrote that they felt a lot more confident in their answers with it. As expressed in the introduction, this was expected; ambiguities in the data that are present in the direct volume rendering are usually resolved during the segmentation process before the indirect volume rendering occurs. An unclear or ambiguous image from DVR can give low-confidence answers that are correct or incorrect, but by the time it is fed to an IVR application, the mesh is already segmented

	Dataset #1						Dataset #2					
	Surgeon #1		Surgeon #2		Surgeon #3		Surgeon #1		Surgeon #2		Surgeon #3	
ID	IVR	C	DVR	C	DVR	C	DVR	C	IVR	C	IVR	C
T1	Post.	M	Post.	M	Post.	H	Ant.	M	Ant.	H	Ant.	H
T2	Caudal	H	Caudal	M	Caudal	L	Same	M	Same	M	Same	H
T3	No	H	No	M	No	M	No	L	No	M	No	H
T4	No	H	No	L	No	H	No	—	No	H	No	H
T5	—	—	—	—	—	—	—	—	—	—	—	—
T6	Yes	H	No	M	No	H	Yes	L	No	H	No	—
G1	4		2		2		3		5		3	
G2	5		3		3		4		5		4	
G3	5		3		—		5		4		4	
G4	5		4		3		2		4		4	
G5	5		4		3		3		4		4	
D1	—		5		4		4		—		—	
D2	—		2		4		3		—		—	
S1	5		—		—		—		1		5	
S2	1		—		—		—		3		5	

Table 6.2: Survey answers color-coded for clarity. The "C" column describes confidence, High, Medium, or Low. For space, posterior is abbreviated to "post." and anterior to "ant.". See task descriptions in Table 6.1 and opinion survey description in Table 6.3.

and any uncertainty resolved, correctly or not. Branches may be missing or connected to the wrong tree. However, when we compared the two visualizations side-by-size with surgeons present, we did not find any clearly visible segmentation errors in this case. Surgeons still reported that they got a clearer idea of the anatomical structure with the IVR tool and would rather use that for surgery preparation. They also wrote that they believe that surgical complications will be easier to predict with the IVR method in particular. From the findings of *Nesgaard et al.* (2017), we know that pre-surgery visualization in general does help reduce complications during surgery.

When it comes to the direct volume rendering, all surgeons wrote that the surrounding tissue gets in the way of the vessels they are looking at, despite my attempts at cropping the volume to the vessels. Improved cropping tools allowing more fine-grained selection could help make cropping more precise and avoiding occluding tissue. While most of the surgeons did not find much value in seeing the surrounding tissue, one surgeon made active use of a visible chunk of the colon to trace and name vessels and expressed that they saw a lot of potential in DVR methods, particularly if the colon could be more clearly visible. The transfer function I used was tweaked for maximal vessel contrast without much regard to the colon as a valuable landmark, and I ignored it completely during segmentation for IVR.

For indirect volume rendering, none of the surgeons made use of the depth-based color-coding. The surgeons would all briefly play with the camera, before setting the camera to a head-on position and then leaving the controls alone. The

ID	Question	Answer DVR #1	DVR #2	DVR #3	IVR #1	IVR #2	IVR #3
G1	I got a clear idea of the anatomical structure of the vessels	3	2	2	4	5	3
G2	I would find this visualization useful while preparing for a surgery	4	3	3	5	5	4
G3	These visualizations have added value over the current situation	5	3	—	5	4	4
G4	With this visualization, potential surgical complications during the procedure are easier to predict	2	4	3	5	4	4
G5	The visualization has value in the operating room during surgery	3	4	3	5	4	4
D1	The surrounding tissue gets in the way of seeing the vessels	4	5	4	—	—	—
D2	The surrounding tissue helps me with spatial orientation	3	2	4	—	—	—
S1	The depth-based color-coding helps me keep track of what vessels are near and far from the camera	—	—	—	5	1	5
S2	The "hatching" effect helps me keep track of which vessels are in front of- or behind others	—	—	—	1	3	5

Table 6.3: Survey for indirect volume visualization. 1: Strongly disagree, 2: Disagree, 3: Neither agree nor disagree, 4: Agree, 5: Strongly agree.

hatching effect went largely unnoticed, and the distance shading options were not used. When the hatching effect was discussed for the purpose of the question asking about their opinions on them, one surgeon was indifferent to it, another didn't find it helpful, and the last though it was a nice subtle effect. The same goes for the distance shading — while they did not use it, two surgeons thought it could be useful, while one did not. Surgeons also expressed that they found the red and blue color coding of the arteries and veins to be very useful, a feature they are familiar with from anatomy textbooks.

In summary, the surgeons I interviewed expressed a preference for the indirect volume rendering tool and felt more confident when using it compared to the direct volume rendering tool. Even so, the IVR tool appear to have given an inaccurate impression of the vessel topology, leading to mistakes in question T6.

Chapter 7

Discussion

In this chapter I discuss the user study results and my thoughts on the surgeons' feedback. I talk about my experiences using the direct volume rendering application, as well as developing my own surface rendering tool for indirect volume visualization.

7.1 Survey

The confident conflicting answers on question T6 are curious, and the reason for the inconsistencies are difficult to pinpoint. I looked over the images side-by-side with one of the surgeons afterwards in an attempt to spot something out of place. Still we saw no immediate issues with the segmentation or transfer function to make the two images diverge significantly. This question was noted by the surgeons to be a difficult one, and it may be that it was biased towards DVR as it provides additional context clues in the form of surrounding organs that the vessels are connected to. While it is also possible the noisy background of other organs and tissue in the direct volume rendering made it look like an extra vessel was there or obscured a vessel from view, the third-party analysis agreed with the conclusions from the DVR. It is unfortunate that no surgeon's notes were available to give us a confident "ground truth" for these datasets.

One participant pointed out that the names of vessels are derived by the organs they feed. By not including the colon in the vessel segmentation process, this presented an additional challenge to locating specific named vessels in the visualization. While ultimately they still expressed a preference for the IVR tool for its clarity, one surgeon stated that they saw a lot of potential in DVR if it could present the vessels with similar clarity to IVR, while retaining some surrounding organs.

As such, an aspect I would like to investigate further for mesenteric vessel visualization is including the colon or other organs being supplied by the vessels in the rendering. In DVR this can be done when setting up the transfer functions and cropping the volume, where neglecting the organs leave them difficult to see if they are present at all. With IVR, this needs to be done during the segmentation

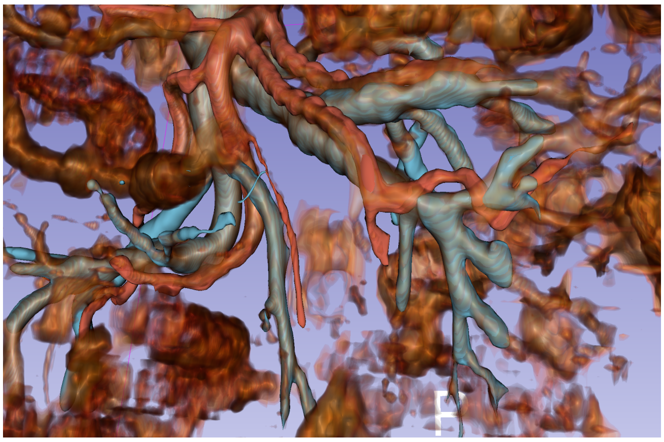


Figure 7.1: Hybrid volume rendering with opaque colored meshes, made using 3D Slicer

process by adding a separate mesh for the organs to provide context information for the vessels.

Alternatively, embedding the segmented mesh in the volume and doing hybrid volume visualization could provide the clarity of the IVR with surrounding context from DVR. However, this may also inherit the downsides of both, requiring the workload of creating both a good transfer function and a good segmentation. This also retains the risk of occlusion issues with DVR, and potential segmentation errors by IVR, but some brief experiments showed promise (see Figure 7.1). The volume rendering can make it easy to spot branches that were missed during segmentation, or show some error margins in the segmentation process. This can be difficult to implement, requiring complex blending between the direct- and indirect rendering passes, or a distinct hybrid volume renderer that also stops raymarching when a ray hits the model.

There are some threats to the validity of this survey. Segmentation errors may have gone unnoticed despite our best efforts, impacting the error rate of indirect volume rendering. So could a poor transfer function for the direct volume rendering. Another issue is the low sample size of surgeons in the survey, as for practicality reasons I have only been able to survey surgeons at the local city hospitals. Another issue is a low sample size of visualizations; as much as it could be useful, only a subset of visualizations methods and techniques were possible to implement in a timely manner. Perhaps a well-adjusted 2D transfer function could significantly improve direct volume rendering quality, or a novel machine learning-based automated segmentation tool would make the workload of creating indirect renderings lower and reduce the chance of human segmentation error in the data.

7.2 Using 3D Slicer for direct volume visualization

3D Slicer provided good visualizations with relatively little work required to adjust the built-in transfer function presets for vascular visualization, and an easy to use cropping tool. In retrospect, these visualizations could have been better if I had spent more time carefully cropping out unwanted features that could block line-of-sight to the vessels.

It is worth noting that the comparison of DVR versus IVR is not “fair”. Similar time and effort could have been put into tweaking and improving the direct volume rendering as was spent on segmenting the vessel tree for the indirect volume rendering. One could also use the segmentation as input for a transfer function for a very clean rendering using DVR. However, the main benefit of DVR in a clinical setting is that it does not require segmentation, and part of the research question for this thesis is whether the added clarity of segmented data results in more confident or accurate reading of the data. This user study indicated that surgeons do feel more confident in their understanding of vascular topology with IVR.

7.3 Using IVRIGST for indirect volume visualization

When using IVRIGST, the surgeons largely left the visualization controls untouched. They would position the camera head-on to the vessels, maybe moving it a bit to build an impression of the topology, before letting go of the controls and writing down their answers. None of the surgeons made use of the depth shading buttons in the indirect renderer, and they gave mixed feedback about the hatching effect.

The two datasets used for the survey had most of the mesenteric vessels oriented on a two-dimensional plane with little variation in depth beyond crossings. This meant there was not much difference in depth to visualize. Depth shading may have been more useful for datasets where the vessels span a larger area on all three spatial dimensions, or with other medical tasks where depth assessment or distance measuring is more important than just being able to tell which vessels are passing in front of or behind another vessel.

The application itself can be a useful tool for prototyping rendering methods. With hot-reloading shaders, a user interface to edit shader attributes on the fly, and easy access to the OpenGL internals, it can be a useful starting point for future projects wishing to experiment with rendering methods. I hope it may be of use by someone else interested in implementing a renderer in a programming language that is seen less frequently in visualization projects. Rust turned out to work quite well for this purpose, as resources intended for working with OpenGL in C or C++ translated more or less directly to Rust. This may serve as a useful educational tool for anyone wishing to get a head start with their own rendering software written in this language.

Chapter 8

Conclusions and future Work

In this thesis, I implement several vascular visualization techniques in a cross-platform visualization tool intended specifically for surface rendering segmented vascular trees. This application and its source code is available for others to make use of or learn from[1]. I have performed a user study with three surgeons, testing clinically relevant tasks using this indirect volume rendering tool and an off-the-shelf direct volume rendering tool. My hypothesis was that IVR methods would be preferred by surgeons, but that it would also cause some false confidence in given answers. Preliminary findings from this user study suggest that this is correct.

8.1 Conclusions

While other research has evaluated the efficacy of individual visualization features, my goal with this thesis is evaluating visualization methods more broadly and with respect to clinical decision-making. I have found that surgeons expressed a clear preference for the clarity of indirect volume visualization methods and felt significantly more confident in their answers when using them, although unfortunately this is the case even when the answers given appear to have been incorrect. IVR may require uncertainty visualization to remedy this false confidence in answers.

While segmentation workload remains a barrier for the clinical viability of segmented indirect volume rendering, this may be remedied with further research in automated segmentation algorithms. Direct volume rendering may also reach similar clarity of images and confidence in answers with further tuning of transfer functions and more accurate cropping. However, there are additional challenges here regarding multi-volume rendering, that may be required to see sufficient contrast in both arteries and veins simultaneously, as these are commonly on separate volumes depending on the timing of the CT scans.

Going forward, it is my opinion that direct volume rendering is currently the more clinically viable method for pre-operative visualization of the mesentery.

[1] https://github.com/stisol/ivrigst

While indirect volume rendering shows a lot of promise and was preferred by the surgeons I interviewed, more efficient segmentation tools or algorithms are required to reduce the workload of these methods, as well as some implementation of uncertainty visualization to avoid false confidence.

8.2 Future Work

As this survey was being limited in the number of participants and available datasets, expanding it to encompass more statistically significant quantities of participants and datasets would be a natural direction of future work. It would also be useful to perform similar surveys with regards to other visualization methods, on different organs, and with respect to other clinical tasks. Another line of enquiry that would be interesting to see pursued further is more prominent use of context organs as discussed in Chapter 7.1. Another direction of future work would be additional surface visual encoding techniques that focus on enhancing the impression of topology specifically rather than depth perception generally for use in visualizing vascular trees.

Appendix A

Survey

Informed Consent — Evaluation of vascular visualization methods.

You are invited to participate in an evaluation of vascular visualization methods. This evaluation is part of a master thesis surveying these methods. During the evaluation you will use 3D Slicer and a second custom tool to answer anatomical questions regarding mesenteric vessel topology. The study will take approximately 40 minutes of your time and the researchers thank you very much for your participation.

If you agree, we will record your interaction with the visualization tools and we will record audio during the whole evaluation session. Participation in this study is strictly voluntary. You may choose to stop participating and withdraw from this study at any time, without providing a reason. Please tell the researchers if you wish to stop.

All the collected data and responses will be handled confidentially, and your name will not be included or in any other way associated with the study if you so choose to. You will receive a copy of these to evaluate whether your feedback has been correctly interpreted or not before we include the results in the thesis.

Consent

I acknowledge that I have read and understand this consent form and I voluntarily participate in this evaluation. I understand that I may stop participation at any time, without providing a reason. If I have any questions or concerns now or in the future regarding the study, I may ask Stian Soltvedt or their supervisor Noeska Smit.

- Name:
- Date:
- Place:
- Anonymous: Yes / No
- Signature:

Tasks

ID	Question	Answer			Confidence		
T1	Does the ileocolic artery pass anterior or posterior to the superior mesenteric vein?	Anterior	Posterior		Low	Med	High
T2	Is the middle colic artery cranial, caudal or on the same level as the GTH?	Cranial	Caudal	Same	Low	Med	High
T3	Is there a right colic vein present with confluence to the middle colic vein?	Y	N		Low	Med	High
T4	Is there a right colic artery present?	Y	N		Low	Med	High
T5	Does the right colic artery cross anterior or posterior to the superior mesenteric vein?	Anterior	Posterior		Low	Med	High
T6	Is an accessory middle colic artery present?	Y	N		Low	Med	High

Table A.1: Tasks.

Survey for direct volume visualization

ID	Question	Answer				
G1	I got a clear idea of the anatomical structure of the vessels	1	2	3	4	5
G2	I would find this visualization useful while preparing for a surgery	1	2	3	4	5
G3	These visualizations have added value over the current situation	1	2	3	4	5
G4	With this visualization, potential surgical complications during the procedure are easier to predict	1	2	3	4	5
G5	The visualization has value in the operating room during surgery	1	2	3	4	5
D1	The surrounding tissue gets in the way of seeing the vessels	1	2	3	4	5
D2	The surrounding tissue helps me with spatial orientation	1	2	3	4	5

Table A.2: Survey for direct volume visualization. 1: Strongly disagree, 2: Disagree, 3: Neither agree nor disagree, 4: Agree, 5: Strongly agree.

Survey for indirect volume visualization

ID	Question	Answer				
G1	I got a clear idea of the anatomical structure of the vessels	1	2	3	4	5
G2	I would find this visualization useful while preparing for a surgery	1	2	3	4	5
G3	These visualizations have added value over the current situation	1	2	3	4	5
G4	With this visualization, potential surgical complications during the procedure are easier to predict	1	2	3	4	5
G5	The visualization has value in the operating room during surgery	1	2	3	4	5
S1	The depth-based color-coding helps me keep track of what vessels are near and far from the camera	1	2	3	4	5
S2	The "hatching" effect helps me keep track of which vessels are in front of- or behind others	1	2	3	4	5

Table A.3: Survey for indirect volume visualization. 1: Strongly disagree, 2: Disagree, 3: Neither agree nor disagree, 4: Agree, 5: Strongly agree.

Preference survey

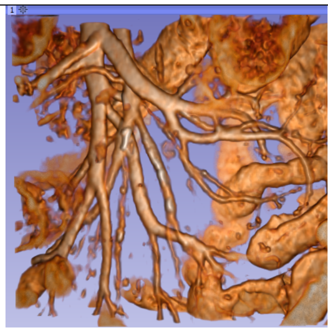
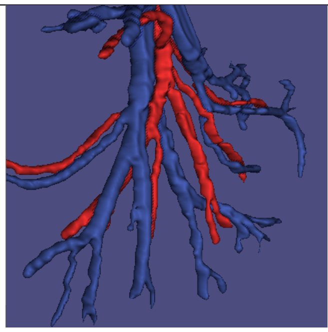
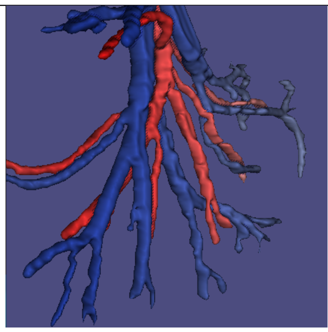
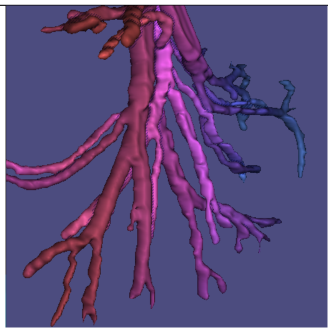
ID	Name	Image	Ranking
V1	Direct volume visualization		
V2	Indirect volume visualization — “Plain”		
V3	Indirect volume visualization — “Aerial”		
V4	Indirect volume visualization — “Color depth”		

Table A.4: Please rank your preferred visualization methods.

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