DE GRUYTER Current Directions in Biomedical Engineering 2022;8(1): 129-132

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Segmentation of Circle of Willis from 7T TOF-MRI data and immersive exploration using VR

https://doi.org/10.1515/cdbme-2022-0033

Abstract: 7T TOF MRI scans provide high resolution images of intracranial vasculature. When segmented, the Circle of Willis is detailed and thus opens up new possibilities, in research but also in education. We propose a segmentation pipeline for the Circle of Willis, and introduce a prototype that enables exploration of not just the entire Circle of Willis, but also of its centerline, in an immersive VR enviroment. In our prototype, the model can be freely rotated, placed and scaled. A qualitative evaluation was performed with two experienced neuroradiologists, who rated the prototype and its potential positively.

Keywords: Circle of Willis, segmentation, VR, anatomy education.

1 Introduction

As technology advances, imaging scans get more and more detailed, revealing a better view inside the human body and its functions. However, with more details, the segmentation of relevant structures from those images becomes more sophisticated as well. 7 Tesla (T) Time-of-Flight (TOF) Magnetic Resonance Imaging (MRI) is a state of the art imaging method, though it is not part of clinical routine yet. It yields high resolution scans that can show even very small vessels with a diameter of $40\,\mu m$ [12]. Such small vessels are important for the exploration of various pathologies, including ones that still need more research to be understood, such as cerebral small vessel disease (CSVD) or arteriovenous malformations (AVM) [12]. Therefore our contribution is to employ such high-resolution scans for deriving geometric models to be used in anatomy education.

Small vessels in the brain are complex structures which are highly relevant for anatomy education and disease diagnosis. The structure of the intracranial vasculature, the Circle of Willis (CoW) is taught in medical education, but is always depicted as a 2D diagram in schooling books, and even most technologically enhanced materials are limited to 2D [7]. This limits the understanding of the CoW's natural alignment and its connections in a real brain. Additionally, a standard CoW does not depict pathologies or prepares for the particularities of patient-specific anatomy. Given that understanding anatomy spatially is one of the most challenging areas for medical students [3], exploring a 3D CoW in VR could thus enhance the learning experience.

2 Materials & Methods

We worked with volunteer data. To obtain the MRI data, a 7T whole-body MRI system from Siemens Healthineers (Erlangen, Germany) with a 32-channel head coil (Nova Medical, Wilmington, MA, USA) was used. For high resolution angiograms the parameters were set accordingly, yielding a final resolution voxel size ranging from $0.26\,mm$ to $0.39\,mm$.

2.1 Preprocessing

To prepare for segmentation and get rid of surrounding tissue, the MR DICOM images were loaded into MeVisLab 3.4.2 [9]. After adjusting page size for faster handling, a vesselness filter was applied multiple times to highlight both larger and smaller vessels. To account for the extreme variations of vessel size, we tested different segmentation strategies. Although a vesselness filter with six scales ($\sigma = 1 - 6$) yields best results, we combined the result image again with a filtered image focusing on small vessels ($\sigma = 1 - 1.5$, 2 scales) and with a filtered image focusing on large vessels ($\sigma = 6$, 1 scale).

Next, a mask was created. The highlighted vessels were segmented with region growing, and a convex hull and dilation was put on the result. This mask was then saved and applied to the vessel image again.

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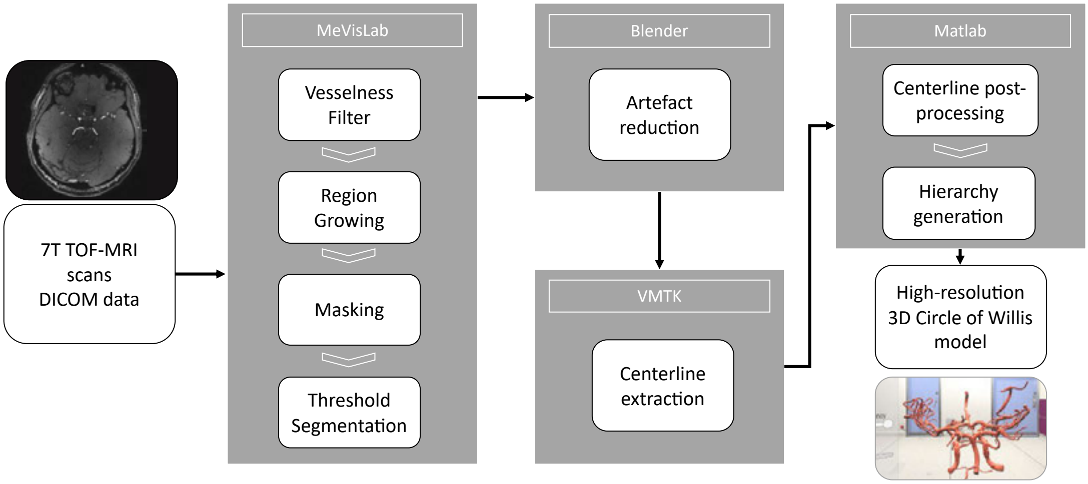

Fig. 1: The segmentation pipeline from the DICOM images to the segmented CoW model, including centerline.

2.2 Segmentation

The background filtered image was then loaded into our in-house software MERCIA, where mesh extraction is carried out as described in [5, 10]. There, a threshold-based segmentation is carried out on the background-filtered image in combination with region growing and connected component analysis to extract the CoW. Special attention was paid to segment the posterior communicating artery (PCOM) in its entirety, as that is a region of interest, as elaborated in Section 3.

The resulting segmentation was then manually edited in Blender 2.93.4 (The Blender Foundation, Amsterdam, Netherlands) to account for fusion, staircase and noise bleeding artifacts from the region growing [5]. Additionally, the periphery was trimmed and inlets and outlets were cut to be approximately perpendicular to the vessel centerline. Finally, the mesh was smoothed manually in Blender's sculpting workspace. A pipeline of the entire segmentation is illustrated in Figure 1.

2.3 Centerline extraction

To prepare for centerline extraction, the CoW's complex 3D model was split at the anterior and posterior communicating arteries into three vessel trees to eliminate cycles. The centerline was then extracted for each of the three subtrees with the Vascular Modelling Toolkit (VMTK) 1.4.0 [2]. The resulting .vtp file was converted into .vtk in Paraview v4.2 (Kitware Inc. and Los Alamos National Laboratory). The .vtk file saves the centerline points, as well as which point is part of which segment, and the maximum inscribed sphere radius for each point.

Matlab R2021a (The MathWorks Inc., Natick, MA, USA) was used to further work with the centerline. VMTK extracts the centerline going from outlet to inlet, meaning each segment ends in the inlet. We algorithmically adjusted number and length of segments so that there is only one segment between two furcations or inlet/outlet. Further post-processing included cleaning up the way segments meet at furcations, deleting wrongly detected segments, and deleting points with a distance of less than 0.1 between them as well as unused points. Unused points refers to points that are not part of any segment.

The hierarchy between the segments was determined, meaning each segment (except the root segment) was assigned a parent vessel. Child vessels were assigned for all non-leaf segments similarly to Saalfeld *et al.*'s [11] flow splitting approach. Hierarchy direction goes from inlet to outlets, thus following the vessel tree from root to leaves. This included recombining the three subtrees into one tree again. Here, the hierarchy direction from root to leaves was followed.

Lastly, vessels with a maximum inscribed sphere radius smaller than 1 were marked as small vessels.

2.4 VR Prototype

The VR environment developed by Allgaier *et al.* [1] in the Unity game engine (Unity Technologies: https://unity.com, San Francisco U.S.) and the XR Interaction Toolkit was used as base for the VR prototype. Their aneurysm selection scene was used as base for a medical environment for the CoW exploration. The CoW model was placed in the middle of the otherwise empty VR OR environment with a menu panel to its left (see Figure 2). The menu contained a slider for transparency and a slider for scale. Transparency refers to the opaqueness of the vessel walls, beneath which the centerline becomes visible (see Figure 3). This can help to show the base structure of

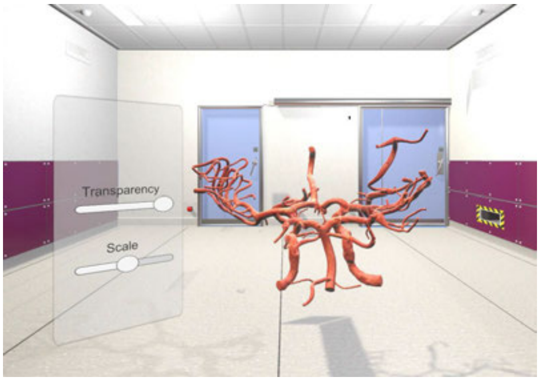

Fig. 2: CoW model in the VR prototype with maximum Opacity and default scale.

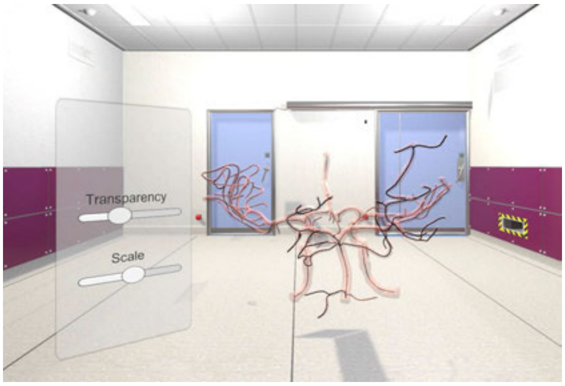

Fig. 3: CoW model in the VR prototype with lowered opacity, showing the centerline.

the CoW without particularities of the vessels and their texture and material in the way. The scale slider can be used to make the CoW and centerline bigger or smaller.

The user can interact with the CoW by grabbing it with the controller. Once grabbed, it can be rotated and placed freely around the room. This way the CoW can be viewed from different angles that would not otherwise be possible.

3 Results & Discussion

The prototype was evaluated with two experienced neuroradiologists and the think-aloud method [4], where the participants were asked to describe their usage and reasonings while testing out the prototype.

They were fascinated by being able to view a CoW at such a big scale. They grabbed and rotated it without having to be prompted, and noted that they had never been able to view it from such angles before. While grabbing and rotating it was their first reaction, they also placed it in the virtual room and then moved in the real space to walk around it. They did not perceive any latency during interaction.

An early comment was how remarkably clear the 3D model made the connection between anterior and posterior circulation, which is usually hard to see. The VR view demonstrated the connection and highlighted that it existed and how the two supply each other. In this context the radiologists repeatedly emphasized how valuable the prototype could be for anatomical education, which corresponds with studies finding that VR enviroments can help convey spatial cues and thus understanding and learning [6, 8].

They also noted that the high resolution of the CoW was helpful, and that an even higher one could be appreciated too, as small vessels that would not usually be shown in most CoW models and diagrams would be visible. Here they spoke of the arteria coroidea anterior, Heubner's artery, the artery of Percheron, and the PCOM, as they could all be important and occlusion could cause severe consequences for a patient.

Inclusion of the centerline was confirmed by the radiologists, as they find the centerline to be the important base structure of the CoW that makes it recognizeable based on just a few lines. They can also further help with access planning for interventions, acting as guidewires through the vessels.

For anatomical teaching, they could imagine a VR CoW model not only helpful for general anatomical education, but also for demonstration of specific pathologies. This is in line with the positive effects noted in surveys on virtual anatomy systems [6, 8].

Additional inclusions would be adding a head and brain to toggle to see orientation of the CoW, and according to the radiologists the eyes in particular to see the distance to them.

In the future, a study to compare how teaching CoW anatomy to medical students with a VR application performs in contrast to the standard education with 2D diagrams would be feasible. While the CoW is a very specialized structure, it is argued that introducing imaging scans much earlier in the medical curriculum than it is currently might help with general anatomical and spatial understanding of anatomy and could have positive consequences [7]. This can help with the mental translation between 2D and 3D, 2D being provided by imaging, 3D by a VR application like our tool.

Another functionality of the application could be a puzzle of complex anatomical structures that can be assembled and disassembled to examine and understand the connections between the parts. This could be done for the CoW, but for other organs too, like the inner ear.

Apart from the VR application, a high resolution CoW that includes centerlines and hierarchies can be useful, for example for computational fluid dynamics, possibly in combination with a prior phase-contrast MRI scan registration. This can help explore hemodynamic parameters and blood flow in patient-specific intracranial vasculature.

In terms of drawbacks, our pipeline relies on four different tools that a user has to be familiar with. Especially the step in Blender requires time-intensive manual work. A streamlined and more automatic approach to integrate these programs into a single framework would be desirable in the future.

4 Conclusion

We segmented a high resolution 7T TOF-MRI scan of the CoW vasculature, including pre-processing and subsequent centerline extraction and post-processing. With the segmented model we developed a prototype VR application that enables exploration of the CoW model, including centerline, in a free 3D environment with a medical OR backdrop. As VR systems have become increasingly affordable in recent years, they have become more widespread. Our prototype includes options for transparancy of the vessel walls and scale of the entire CoW model, as well as freedom to rotate the CoW around all axes and place it within the room.

The prototype was rated very positively by neuroradiologists, who commended the educational possibilities of such a VR application and saw further potential for other use cases.

In the future, we aim at an automatization of the segmentation pipeline including a quantitative study comparing education with a VR model in comparison to standard 2D diagrams.

Acknowledgment: We thank Dr.-Ing. Hendrik Mattern (Department Biomedical Magnetic Resonance at the Otto-von-Guericke University Magdeburg) for the 7T MRI data.

Author Statement

This work is partly funded by the Federal Ministry of Education and Research within the Forschungscampus *STIMULATE* (grant no. 13GW0473A) and the German Research Foundation (SA 3461/3-1). Authors state no conflict of interest. Informed consent has been obtained from all individuals included in this study. The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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