

3D Printing of the Cerebral Vasculature Exceptionally Using Freeware – A Quick and Easy Guide

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Abstract

High-resolution 3D reconstructions of the cerebral vasculature are essential for preoperative planning of complex interventions in vascular neurosurgery. Quick-segmentation algorithms provided by expensive radiology applications often result in unsatisfactory 3D reconstructions. Here we show how to quickly segment and print a detailed 3D model of the cerebral vasculature without extensive knowledge in 3D modeling. Exceptionally using freeware, the total costs for the generation of a real size model of the circle of Willis are less than \$10. The 3D models will be particularly valuable during preoperative planning and for patient information.

Introduction

In order to treat complex diseases of the cerebral vasculature, precise high-resolution imaging is indispensable. Medical slice imaging is usually provided in three orthogonal 2D planes for diagnostic evaluation and surgical planning. The anatomically complex structures of the cerebral vasculature with their close relationship to crucial structures such as cranial nerves, brain parenchyma and the skull base require precise 3D imaging. In most cases, 3D reconstructions are provided by the hospital's radiology department. However, these 3D reconstructions only represent a few snapshots of a 3D model, which can be scrolled through in only one given direction. These conventional 3D images have major disadvantages. Often the quality of the 3D reconstruction is insufficient when using quick-segmentation algorithms of common radiology applications. 3D segmentation can be very time-consuming and a lot of knowledge about the upcoming surgical procedure is needed. Because the surgeons know best which structures are of particular interest, they should be involved in 3D segmentation and modeling. Until now, 3D segmentation of Digital Imaging and Communications in Medicine DICOM data has been laborious, required advanced knowledge in the use of non-intuitive software and required considerable financial expenditure to acquire the corresponding licenses.

3D printing is currently a big hype and 3D design and printing is widely used in virtually all industries and as a hobby of millions of private users around the globe. As a result, numerous 3D segmentation and design programs are currently available for use. In the spirit of the 3D community, many of the applications are open-source and can be downloaded for free. In addition, these applications are very easy to use and there are instructional videos online for almost any problem to be encountered.

In surgery, the advances in 3D printing technology have sparked a revolution. 3D models improve the surgeon's anatomical understanding in surgical planning^{1,2} surgery time can be shortened, blood loss reduced and the outcome improved^{3,4}.

Here we show how any practitioner can create a high-quality 3D reconstruction of the cerebral vasculature based on standard MR imaging in very short time and without advanced knowledge in 3D segmentation. The 3D segmentation is performed exceptionally using freeware and therefore is

affordable for everyone. We also provide instructions on how to create a 3D print of the circle of Willis in original size from a 3D mesh.

Materials And Methods

1. Data acquisition

Gadolinium contrast-enhanced time of flight TOF 3D MRI sequences were used as a basis for segmentation of the cerebral vasculature. Data acquisition was performed on a Siemens Magnetom MRI device. Imaging data has been converted to DICOM files for further processing.

2. Segmentation of the cerebral vasculature

3D Slicer, an open-source platform for analyzing medical image data (www.slicer.org) was used to segment the cerebral vasculature from contrast-enhanced TOF 3D MRI sequences. After having launched 3D Slicer, DICOM files were imported into the DICOM browser of 3D Slicer by simply drag and drop the DICOM files on the “Load DICOM Data” button. The DICOM browser will open automatically and the correct Patient, the study (MRI) and the series (TOF 3D Gadolinium) was chosen, proceeded by pressing load button. The main window of 3D slicer will open depicting the MRI dataset in all 3 planes axial, coronal and sagittal. “Segment Editor” was opened in the module list. By pressing the “+Add” button a new segment was created and the new “Segment_1” appeared in green color. The cerebral vessels are bright white in contrast-enhanced TOF 3D MRI slices, while the brain parenchyma and the skull are grayish. In order to take advantage of the intensity difference the threshold function was launched by pressing “Threshold” button which allows to set a threshold range by shifting both the minimal and the maximal value slider. The selection can be controlled in real time in all 3 planes. As the contrast-enhanced vessels are the most intense structures in the scan, the maximal slider was set in maximal top right position. The minimal slider has to be adapted: Around intensity values of 150 the skull, the orbit and some of the brain parenchyma will be selected. After 200 there are muscles, orbital vessels and the mucosa of the paranasal sinuses left. Up to 300 it is not possible to differentiate the cavernous segment of the internal carotid artery from cavernous sinus. With even higher settings, the selection is more specific for cerebral vasculature but you will start losing selection of small arterial branches from A/M/P 3 upwards. Therefore, a minimal threshold value of 300 was set as a right compromise. This lower threshold value may vary depending on what system or sequence is used. For contrast-enhanced T1 sequences, the lower threshold level is considerably higher compared to TOF Gadolinium, because brain parenchyma appears in a lighter shade of gray. Values of around 700 will work for T1 Gadolinium sequences. By pressing the “Show 3D” button a 3D reconstruction was generated. In order to get rid of any vessels not connected to the circle of Willis the “Islands” tool was used. The application of the “Keep largest island” function was resulting in a pretty decent 3D segmentation of the cerebral arteries forming the circle of Willis up to the M4 branches (Fig. 1). Unwanted structures such as the greater vein of Galen, parts of the sigmoid sinus and branches of the external carotid artery were then cropped by using the scissors tool in the modus “erase inside” where you can draw circles directly in the 3D reconstruction

window. Finally the 3D reconstruction had to be exported as a 3D model in a printable file such as stl, vtk or ply. To do so, “Data” was chosen in the module list and on the left, the hierarchy tree showed up. A right-click on “Segment_1” allowed to choose “Export visible segments to models”. With the “Save” button the 3D model was saved as an stl file.

3. Geometric surface preparation

3.1. Meshmixer

The 3D model was imported into Meshmixer (www.meshmixer.com), a freeware for working with triangle meshes by pressing “+Import” and selection of the corresponding file. Unwanted branches could be easily selected with the selection tool and showed up in orange color. By pressing “x”-key the selected parts were deleted (Fig. 2). Then the mesh was automatically inspected in order to fill holes and close the surface by pressing “Analysis -> Inspector-> Auto repair all”. All of these functions are embedded in Blender software as well but the use of Meshmixer is way more intuitive for the 3D-beginner.

1. Blender

Blender, an open-source 3D computer graphics software (www.blender.org) was used for further surface preparation. The stl file previously modified in Meshmixer was imported by choosing “File -> Import -> Stl”. Then the mesh was smoothed either by going to the Edit Mode with tab key and pressing “smooth” in the tools selection bar or by adding “Smooth” or “Laplacian Smooth modifier”. In order to display the model, a cube was created by choosing “Add -> mesh -> cube” and the cube was scaled by pressing “S” key to fit below our model. The patient’s case number was engraved on the stand by adding a text (Add -> Text) in Edit mode (Fig. 3). To save computing power, the number of vertices was reduced with decimate modifier (Add Modifier -> Decimate), a ratio of 0.5 which reduces the vertices by half was applied. Finally, the optimized model was exported as a new stl file (File -> Export -> Stl).

4. 3D printing

The model was printed using an Ultimaker 3 dual extruder 3D printer (www.ultimaker.com). The definitive stl file was imported in Cura software (ultimaker.com/software/ultimaker-cura). Red polylactic acid PLA was chosen for printing the vessels and the stand. The water-soluble polyvinyl alcohol PVA filament served as a support filament in order to print overhanging structures. The print was performed at a layer thickness of 0.15 mm. After printing, PVA supports were dissolved in water during 24 hours and the final model was dried at ambient temperature (Fig. 4).

Discussion

3D modeling starts with data acquisition. Every modality of 3D medical imaging such as MRI, CT, CTA, MRA, DSA or PET is suitable for 3D printing. The medical dataset is usually stored as a DICOM (Digital Imaging and Communications in Medicine) file. For cerebral vasculature, the best resolution would be

obtained by using 3D reconstructions of cerebral angiographs⁵. If angiography imaging is used, the disadvantage is that only the supply area of one cerebral vessel is depicted at the same time. Therefore, angiography data sets are not suitable for the reconstruction of the circle of Willis. We decided to select DICOM files of contrast enhanced Time of Flight TOF sequences which are part of our standard MRA protocol.

Next, a 3D reconstruction has to be generated using slice imaging data. Applications like 3D Slicer are able to do this automatically. From the 3D reconstruction of the entire dataset, the structure of interest is selected or so called segmented. This step requires medical knowledge to identify the correct structures. Ideally, the surgeon himself will perform the segmentation which allows him to focus on areas of interest and to prepare for the upcoming surgical procedure. Segmentation is already a field for the application of artificial intelligence AI but the freeware available is scarce and manual modifications are still needed today. 3D Slicer is a freeware that allows the conversion of DICOM data into multiplanar and three-dimensional data sets. With the segmentation tool "Segment Editor", the cerebral vessels can be most easily extracted based on the difference in intensity compared to brain-parenchyma in the TOF gadolinium sequence using the "Threshold tool". The "Island tool" results in the removal of non-connected structures within seconds and cleans the mesh. This completes the segmentation and the 3D model can be exported as a Standard Tessellation Language STL file. The next step is dedicated to geometric surface preparation. The mesh must be closed, overlapping surfaces removed and holes filled. These steps can easily be performed in Meshmixer. The Analysis-Inspector tool automatically corrects the mesh and prepares it for printing. Furthermore, Meshmixer allows to select and delete undesired structures in a very quick manner using the selection tool. Geometric surface preparation can be performed entirely by using Blender, but Meshmixer is far more intuitive to use for the 3D beginner. To smooth the mesh, we used the sophisticated Laplacian smoothing modifier in Blender to get the best results. To simplify further processing and save computing power, the number of vertices of the surface mesh must be reduced without losing detailed information. For this purpose we used the "Decimate Modifier" in Blender. With the preset ratio of 1.0, 100% of vertices will be preserved, but in most cases you will be able to decimate the vertices by half without losing relevant detail. Therefore, we recommend to choose a ratio of 0.5 which will efficiently facilitate further operations. After optimizing the mesh, the 3D reconstruction can be exported again as a new stl file. For 3D printing, the final stl file is imported into a printing application. The print software virtually aligns the model on the corresponding print platform and you are able to set the parameters for printing. We are using the freeware Cura (<https://ultimaker.com/software/ultimaker-cura>) for this purpose. Our model was printed in red polylactic acid PLA with an Ultimaker 3 double extruder filament printer. The printer reaches a maximal resolution of 0.06 mm layer thickness. For our purpose, a layer thickness of 0.15 mm was sufficient. As a support filament we used polyvinyl alcohol PVA which is conveniently water-soluble. PLA is a thermoplastic material with a high-melting point of around 250 °C and is suitable for steam sterilization at 121 °C. The total costs of our model of the Circle of Willis are very low, because we exceptionally use freeware. Therefore only the material has to be paid, the price for PLA and supporting filament was below 10\$ in our example. There are some one-time costs

for the printer, in our case they amounted to approximately 4000\$, whereby there are also some much cheaper models available for a few 100\$. Alternatively, printing can be outsourced to a print service.

Conclusions

The presented workflow can be used by any practitioner to quickly generate precise 3D models of the cerebral vasculature based on standard DICOM data without advanced knowledge in 3D designing and without spending money on licenses. 3D printed models allow a more intuitive understanding of complex anatomical structures or pathological processes⁶. The 3D models will be particularly valuable during preoperative studies as well as for patient information.

Declarations

Ethics declaration and consent to participate:

Ethics declaration NA. Written consent to participate was obtained from the patient.

Consent for publication:

Written informed consent was obtained from the patient for publication of this technical note and accompanying images.

Availability of data and materials:

The datasets generated during the current study are available from the corresponding author on reasonable request.

Competing interests:

The authors declare that they have no competing interests.

Funding:

None.

Authors' contributions

AK performed the segmentation, mesh generation and 3d print model. All authors read and approved the final manuscript.

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Figures

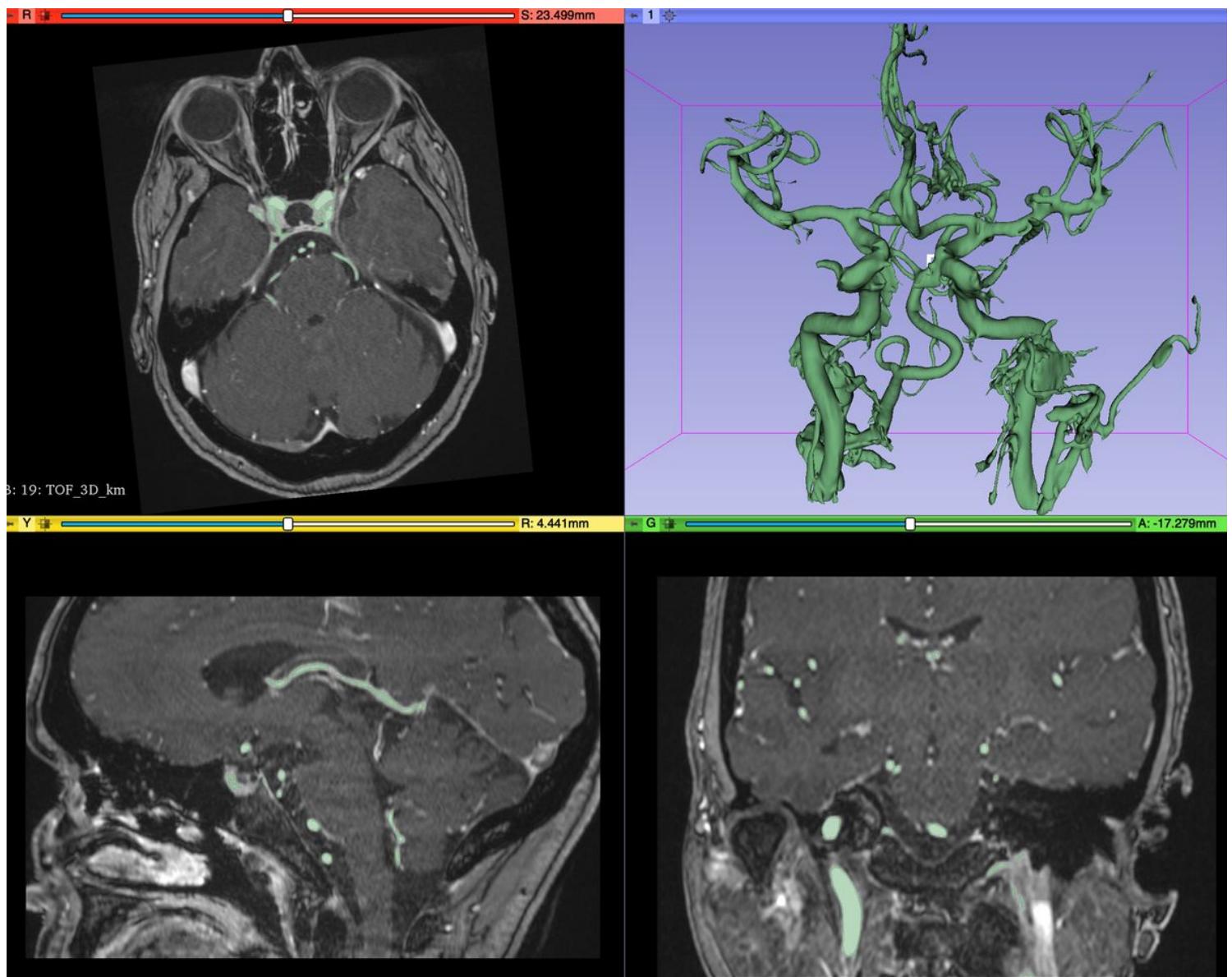


Figure 1

Segmentation of the cerebral vasculature using DICOM data of a contrast enhanced TOF 3D MRI sequence using 3D Slicer.

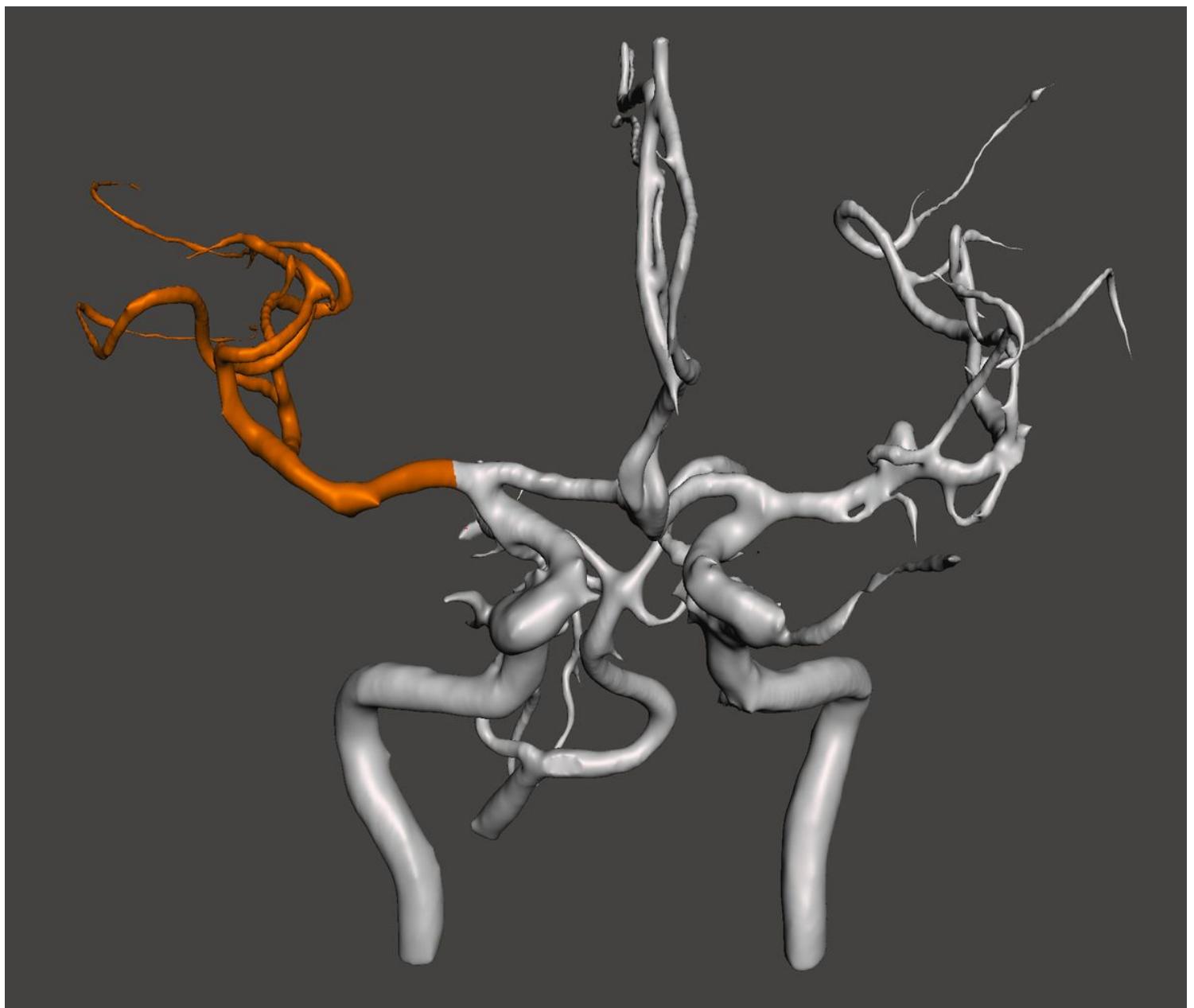


Figure 2

Easy selection of vessel branches to optimize your model and mesh closure using the inspector tool in Meshmixer.

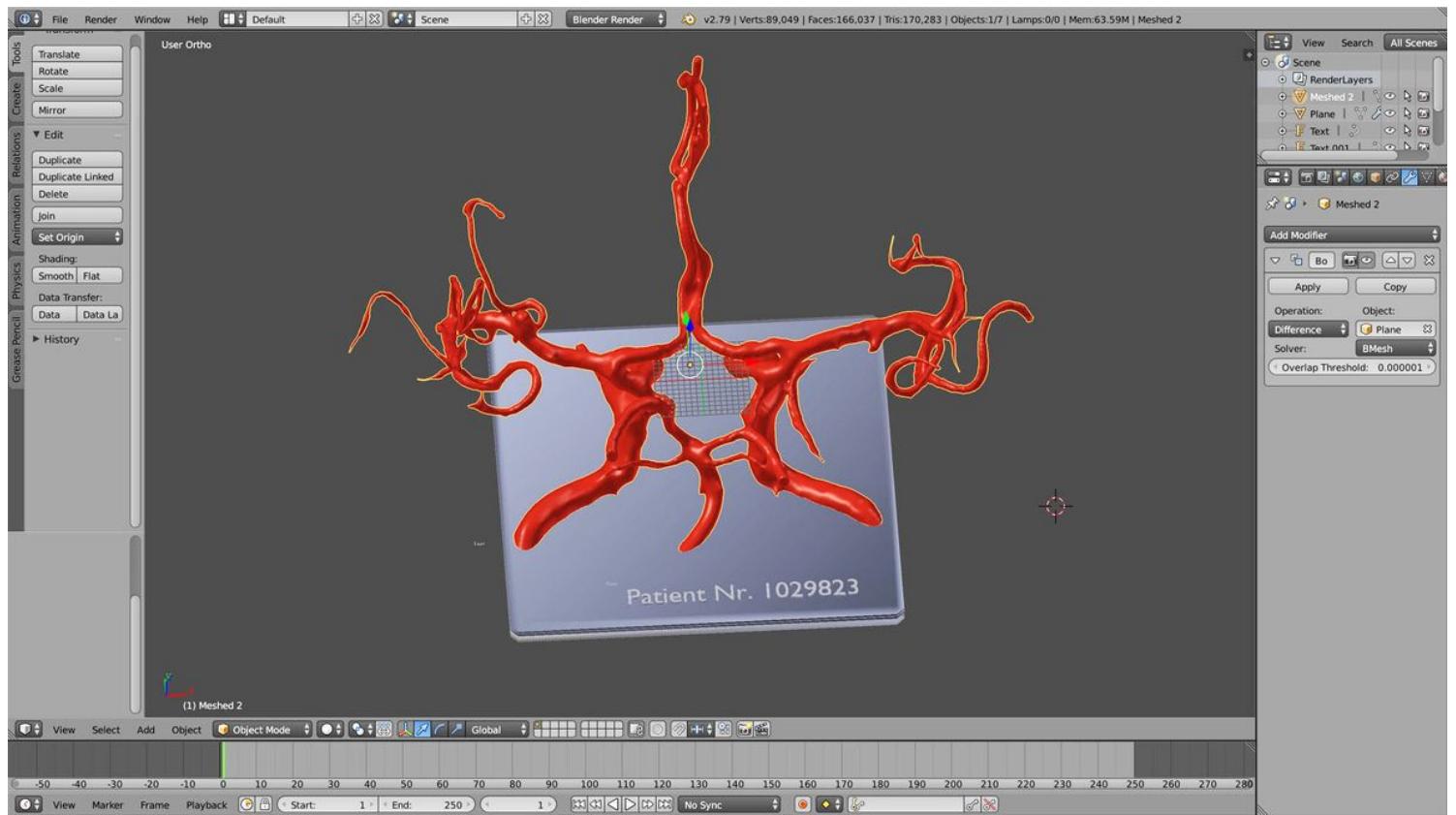


Figure 3

3D reconstruction of the cerebral vasculature smoothed in Blender with construction of a little stand and engraving of patient number.

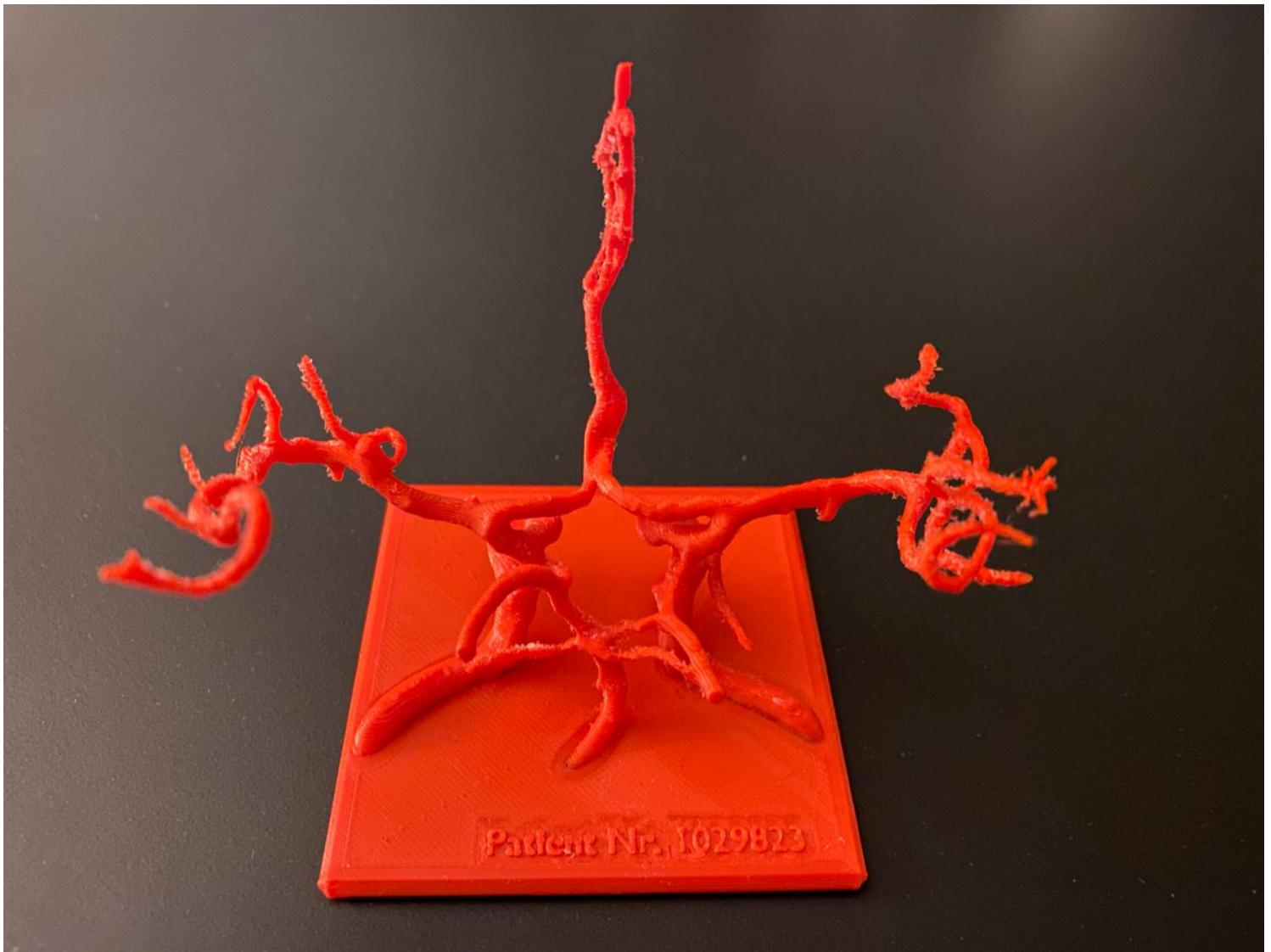


Figure 4

3D printed 1:1 model of the cerebral vasculature in red polylactic acid PLA after dissolving polyvinyl alcohol PVA support.