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Modelling of Human Cerebral Blood Vessels for Improved Surgical Training: Image Processing and 3D Printing

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ABSTRACT Human cerebral blood vessels are highly intricate and significantly contribute to brain function support. In the surgical process of these vessels, the neurosurgeons will basically employ magnetic resonance imaging (MRI) as an imaging media to understand the location of the disorder, the anatomical position of vessels, and a guide in the surgical process. However, the usage of MRI data remains a challenge for surgeons in understanding anatomical structures in greater detail, as well as the limitations of training in handling difficult cases. This study aims to provide further technology, combining three-dimensional (3D) image models and 3D printing to accommodate the lack of visualization and pre-operative simulation using MRI data. First, the MRI data would be exported to a software 3D slicer that has the ability to process images with a threshold method to segment the required body parts and generate 3D models. Then, the 3D model of blood vessels would be imprinted using the SLA method to provide the complex anatomical structures of blood vessels. The results from both 3D image modeling and 3D printing have been validated and have dimensions similar to those of the MRI data, indicating that this work is highly accurate. This work significantly helps the surgeons to have a better plan for the surgery steps, identify potential issues before the procedure begins, and develop more precise approaches.

INDEX TERMS Brain Blood vessel, Pre-Operation, Image Reconstruction, Fused Deposit Modeling, Stereolithography Apparat

I. INTRODUCTION

The blood vessels in the human brain are a very complex network, playing a crucial role in supplying oxygen and essential nutrients to the brain[1]. The circulatory system consists of three main components: veins, arteries, and capillaries. The main arteries, such as the carotid arteries and vertebral arteries, branch off from the anterior, middle, and posterior cerebral arteries. The venous structure is also highly complex as they connect with the dural sinuses, which serve as large channels for collecting blood from the entire brain. Arteries have a narrower lumen than veins, which helps regulate blood pressure throughout the body. Because the blood vessel walls are thin and their proximity to the brain complicates matters, precise navigation is crucial during medical treatment [2][3].

In this vascular surgery process, the neurosurgeon will essentially use magnetic resonance imaging (MRI) as an imaging medium to understand the location of the disorder and the anatomical position of the blood vessels, as well as a part of the surgical procedure. There are some diseases that affect the blood vessels in the human brain, such as cerebral aneurysms, arteriovenous malformations (AVM), and carotid artery stenosis [4][5]. Having understanding and in-depth knowledge of anatomy is crucial for accurate diagnosis [6], [7]. Koizumi S et al. demonstrated that 3D models can be beneficial in understanding diseases and exploring complex neurosurgical procedures [8]. Karakas et al. highlighted that 3D modeling and 3D printing provide a good strategy for conducting comprehensive study revisions [9]C. Ploch et al., they underscored the value of realistic models that incorporate physiology, anatomy, and tactile feedback, enabling medical practitioners to practice intricate procedures and enhance treatment plans beyond the scope of two-dimensional images [10]. Randazzo et al. assert that in neurosurgery, 3D models facilitate the visualization of intricate vascular structures, allowing for more accurate surgical techniques and minimizing the potential for damage to adjacent tissues[11]. The process of learning anatomy generally uses two-dimensional atlases, which are difficult to reflect the spatial structure and real relationships between organs. Additionally, the strategy for improving surgical education is through direct learning via case studies.

In the cerebral vasculature or the system of blood vessels in the brain, it consists the complex structures that function to provide the nutrients, oxygen, and glucose that necessary for the functioning of the central nervous system (CNS), neurons, and glial cells [12]. Another diseases in the vascular brain system, called cerebral small vessel disease (SVD), is a condition affecting the blood vessel in the brain that, if left untreated can lead to lacunar strokes and intracerebral hemorrhages [13]. In SVD, many parts of the vessels are at high risk, necessitating careful pre-operative planning and good training objects before surgery is performed. Cadaver dissection is the most important approach in understanding the location of key topographic points and illustrating three-dimensional anatomy. In recent years, the number of available cadavers has not been sufficient to meet the various educational needs. Iwanaga et al, identified a number of significant limitations in traditional cadaver dissection methods, including ethical issues, limited availability, high maintenance and storage costs, and health risks associated with the use of formalin[14].

The technique of plastination, computer-based learning, and medical imaging are very suitable for application in the study of body anatomy and pre-surgical education [15]. 3D visualization technology has proven effective in human anatomy learning and opens up opportunities to explore various potential factors that can influence training outcomes, thereby providing better guidance in anatomy teaching as well as surgical training. With this technological advancement, the learning process has become more interactive and allows medical students or doctor to understand the complexities of human anatomy in a deeper and more comprehensive way. To increase the quality and effectiveness in SVD diagnosis, a better understanding of pathogenesis monitoring of SVD through MRI imaging are essential. Advanced structural imaging techniques, including diffusion MRI, can be developed into 3D visualization, allowing for better detection of vascular tissue damage [13].

3D visualization, the anatomical structure of the human body, especially in the head area focusing on the brain's blood vessels, can be rotated, flipped, and viewed in detail from various angles. After 3D visualization, the 3D model can be printed, so the new 3D printing models could be considered more promising as a learning and pre-operative medium because they are more accessible [16]. In addition, to deepen understanding, the application of physical 3D printing technology allows the creation of physical models of complex anatomical structures, alleviating pre-operative difficulties for doctors and providing a more realistic and tactile learning experience for students [17][18].

This study aims to build a physical model of the patient's specific organ on human cerebral blood vessels, that expects to assist as pre-operative planning before surgery [19]. The application of three-dimensional (3D) models in the clinical field has proven to be one of the effective applications in improving medical procedures. According to Bai et al., the use of 3D models can result in shorter operation durations, reduce intraoperative blood loss, and accelerate patient recovery times [20].

II. METHODS

The method used in this study consist of image acquisition, 3D model construction, and 3D printing. This study employs 3D slicer software to process medical imaging data and to develop the 3D model [21], [22]

A. PATIENT SELECTION

This research uses 10 MRI image datasets obtained from hospitals. The data used from 2015 to 2019 consisted of 8 arterial images and 2 venous images with case studies diagnosed with tumor diseases. The data used has obtained ethical approval such as ethical clearance. (EC). In the implementation of this research, the aspects of confidentiality and data security of patients are strictly maintained with access restrictions [23]

B. IMAGE ACQUISITION

The equipment used is a magnetic MRI performed using a GE (General Electric) 1.5 T magnet machine from a local hospital. Performa the MRI is employing a three-dimensional phase-contrast MRV method. This scan included both T1 and T2 axial images. The MRV was performed with a three-dimensional phase-contrast technique, featuring a velocity encoding of 15 cm/s, a repetition time of 25 ms, a flip angle of 20 degrees, and an echo time of 7.2 ms. The original image has dimensions of 696 x 768 x 136 pixels with a file size of 0.06 MP. This image is reprocessed to a size of 512 x 512 x 136. The standardization of this size is applied to optimize the computation process. The data obtained is specific to the head organ, and the scanning process takes approximately 1 hour to complete. These details are crucial for ensuring the accuracy and quality of the images for medical diagnosis [24].

C. 3D MODEL RECONSTRUCTION

Enhancements in image quality can be achieved in two ways: through contrast enhancement and non-contrast enhancement. The function of contrast enhancement is to clearly see thin parts of organs and to sharpen the image. Increasing image contrast can be done in 3D Slicer software. In this method, the software used is Slicer. 3D Slicer is a free software for medical image computing. The way 3D Slicer works is similar to radiology, which can read image visualization, surgical navigation, Graphical User Interface (GUI), and segmentation. This device has many features that can be used, one of which is for image processing [25].

TABLE 1
Hounsfield of human organ [27]

Item	HU
Bone	200 – 3000
Blood (With Contrast Agent)	100 – 500
Blood (Without Contrast Agent)	40
Liver	40 – 60
Muscle	10 – 40
Fat	-50 - (-100)
Air	-1000

In the volume feature and can then be adjusted in the window width (WW) and window level (WL) sections. For blood vessels, to enhance contrast, settings between 400 WW and 250 WL can be applied. The settings for each patient's data vary, so they can be adjusted according to the patient's results. In addition to improving image quality, it is necessary to enhance the Hounsfield. (HU). Table 1 explains the HU values for each human organ. This is because denser materials absorb more radiation compared to softer materials [26]. Image segmentation involves applying a threshold to the transformed image to segment it. To keep the method automatic, it is important to apply the threshold to the maximum value n, so that only the pixels that are segmented for all are considered. The purpose of image thresholding is to divide a set of pixels based on their grayscale levels. The basic principle of thresholding segmentation is as Eq. 1 [28] :

$$g(x,y) = \begin{cases} E\_A, & f(x,y) \in E \\ E\_B, & others \end{cases} \quad (1)$$

The basic principle involves using a threshold value (Z) to classify pixels into either the object or the background. The function (F(x,y)) represents the grayscale level of a region in the image, and (E) represents the chosen target grayscale level and background level [28]. The basic principle involves using a threshold value (Z) to classify pixels into either the object or the background. The function (F(x,y)) represents the grayscale level of a region in the image, and (E) represents the chosen target grayscale level and background level [28] .

Visualizing small blood vessels, high-resolution DICOM MRI data scans are used to identify structures within the skull. FIGURE 1. (A) shows DICOM data from the venous sinus dural vessel, marked in white. The process of separating blood vessels is carried out by selecting the desired area or region of interest (ROI) [29], where the determination of the ROI is done through the observation of Hounsfield Units (HU) to clarify the area to be analyzed. FIGURE 1. (B) shows the results of blood vessel segmentation using the threshold method.

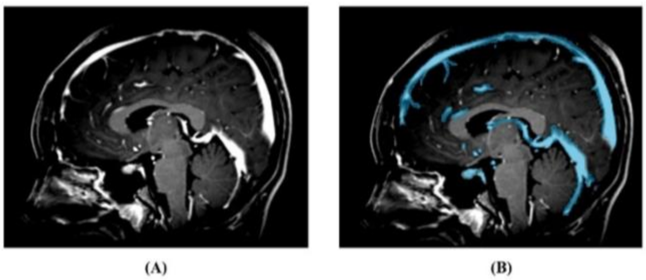


FIGURE 1. (A) Original DICOM Vein (B) Segmentasion DICOM Vein

Segmentation of arteries and veins in brain blood vessels can be performed using two methods: the manual method and the threshold method [10]. Both methods have their advantages and disadvantages. The manual method relies on direct marking by the user with the help of a paint tool feature. This process is carried out in detail and step by step for each image slice, allowing users to adjust the segmentation based on direct visual observation. In contrast, the threshold method is a basic segmentation technique that automatically divides images based on pixel intensity [11].

FIGURE 2. shows the original MRA, pre-processing, vessel segmentation stage, and the 3D model uses the threshold method for segmentation, with a threshold value range of 250 to 900. This segmentation feature is available in the 'Segmentation Editor,' which facilitates the adjustment process. The set threshold value helps distinguish blood vessels from the surrounding tissue. This feature can be found in the 'Segmentation Editor,' with the threshold value set between 250 and 900. While this approach is more time-efficient, it is less flexible in handling the complex variations of blood vessel structures as it solely depends on pixel intensity.

Evaluating the results of segmentation can be done using the following metrics Eq. (2) [30]:

1. *Dice Index*: The Dice Index evaluates the overlap between two segments in 2D or 3D and provides a value between 0 and 1[28] .

$$D\,(A,B) = \frac{2\,|A \cap B|}{|A| + |B|} \quad (2)$$

   where A and B are the two sets to be evaluated.

2. *Hausdorff Distance* (HD): This measures the difference between two sets of points by calculating the maximum distance between points in set A and set B

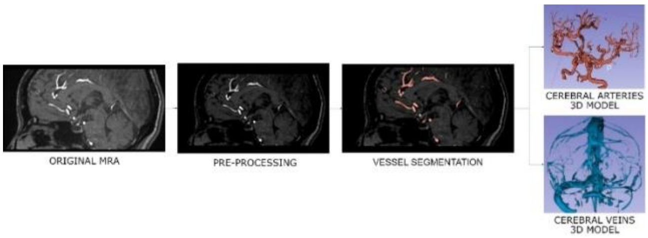


FIGURE 2. Segmentation Method for 3D Model Reconstruction

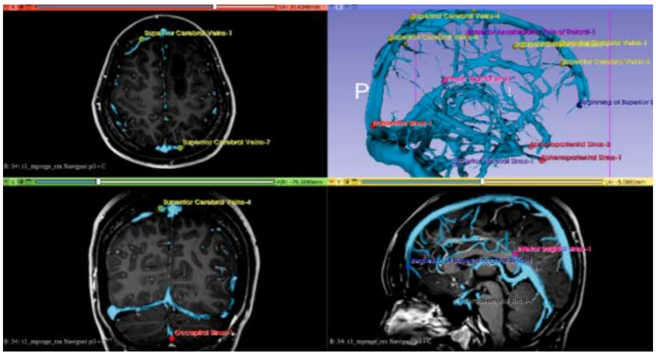


FIGURE 3. venous vessel labeling

The process of labeling blood vessels in a three-dimensional brain model is crucial for enhancing the clarity and utility of medical imaging data[31]. The Fiducial Registration Wizard in 3D SLICER is a specialized tool intended to align and synchronize positions among diverse three-dimensional medical datasets. FIGURE 3. illustrates the outcomes of the venous vessel labeling. The labeling process begins with the addition of marker points on anatomical structures such as blood vessels. Each label added significantly facilitates the identification of relevant organs and blood vessel structures, especially when analyzing complex medical data. This process is systematically repeated to ensure comprehensive coverage of all important vascular structures. The accuracy in label placement is very important, as it directly affects the effectiveness of the model in medical applications and research.

D. 3D PRINTING

Additive manufacturing, also referred to as three-dimensional (3D) printing technology, has spurred important advancements and produced excellent prospects for numerous scientific domains [32]. 3D printing has been utilized in the field of biomedical engineering as a model for the creation of surgical instruments and bones for precision medicine. Equipment made with 3D printing is often intended to be used as teaching aids and learning media [33][34]. Using modern technology, such as 3D printing, to create detailed renderings of anatomical variances that are easy to identify is one way to improve the educational experience and make it a desirable investment [35]. Due to their ease of availability, 3D printed models are thought to be more promising as a teaching tool [16]. Models that closely resemble the real human body parts may now be made with 3D printing techniques, making the task obsolete. The head, which includes the skull, brain, and blood vessels, has an extremely complicated anatomical structure. Printing techniques that are most frequently employed are SLA (Stereolithography Apparatus) and FDM (Fused Deposition Modeling).

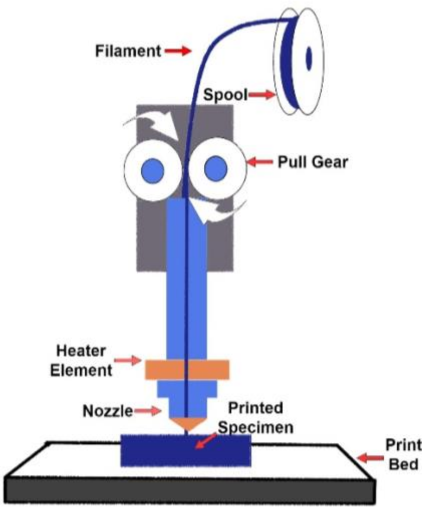


FIGURE 4. **Fused Deposit Modeling Method**

1) FDM (FUSED DEPOSITION MODELING)

The fused deposition modeling (FDM) technique uses slicing or layer printing processes to create three-dimensional objects from digital models as shown in FIGURE 4. The FDM process commonly uses PLA, PETG, TPU, ABS, ASA, and PVA as materials. Filament materials are recommended as materials that make it easier to remove support from complex objects. A synthetic semi-crystalline substance with thermoplastic properties and hydrophilicity is called polyvinyl alcohol (PVA). The polymer is generated by hydrolyzing poly(vinyl acetate), making it biocompatible, water-soluble, and exhibiting changing characteristics like melting temperature (Tm) or viscosity depending on the degree of hydrolysis [36]. The nozzle of a 3D printer functions as a heater that turns the filament into a liquid form [37]. It is advised to utilize nozzle diameters of 0.3, 0.4, 0.6, and 0.8 mm in FDM printing for blood vessels, with a heating temperature of 190 °C [38][39]. PLA filament is the printing material used in the Bamboo X-1 Carbon 3D printer process. The specifications of this printer are delivered in the Table 2.

TABLE 2
Specifications of the Bamboo X-1 Carbon Printer [40]

Item	Specifications
Build Volume (W*D*H)	256*256*256
Nozzle	Hardened Steel
Max Hot End Temperature Nozzle	300 °C
Filament Diameter	1.75 mm
Build Plate	Flexible Steel Plate
Max Build Plate Temperature	110 °C@220V, 120 °C@110V
Max Speed of Tool Head	500mm/s
Max Acceleration of Tool Head	20m/s2
Physical Dimensions	389*389*457mm
Net Wieght Dimensions	14.13kg
Voltage	100-240 VAC, 50/60Hz
Max Power	1000W@220V, 350W@110V

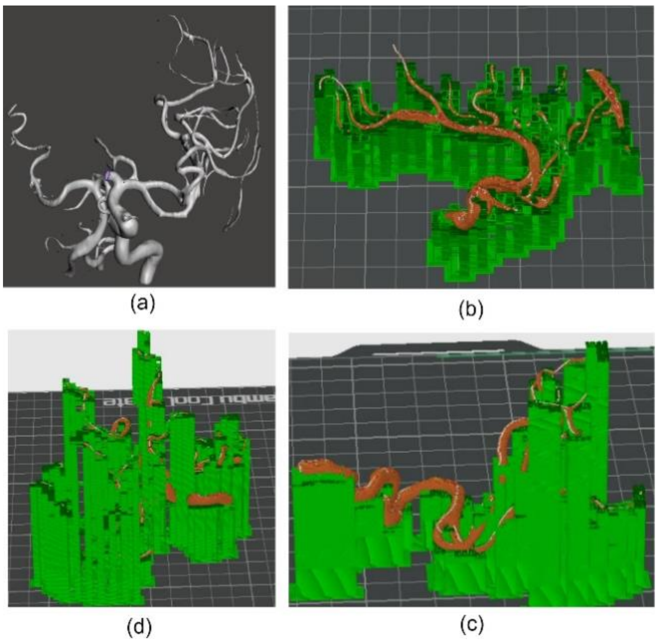


FIGURE 5. **Pre-processing FDM Method (a) Arterial Blood Vessel Autodesk Meshmixer (b) Arterial Blood 3 Middle Section (c) Arterial Blood 3 Right Section (d) Arterial Blood 1 Left Section**

The most straightforward printing technique involves printing an entire 3D model at once, although it has restrictions depending on print size, among other factors. The size may surpass the print dimensions if the model's proportions correspond to those of the real organ. As seen in FIGURE 5. (a), the FDM printing process is broken down into multiple steps to make it easier to remove supports and intricate details that are challenging to print with Autodesk Meshmixer. Utilizing Bamboo Lab software, the cerebral artery FDM OBJ printing is carried out. In order to facilitate printing, it is divided into three sections: the center artery in FIGURE 5. (b), the right part in FIGURE 5. (c), and the left portion in FIGURE 5. (d).

2) SLA (STEREOLITHOGRAPHY APPARATUS)

The stereolithography apparatus (SLA) method is a 3D printing process that uses ultraviolet light (UV). Photopolymer, a liquid resin that solidifies in the presence of ultraviolet (UV) light, is the printing substance used in SLA. FIGURE 6. depicts the SLA's working methodology[41].

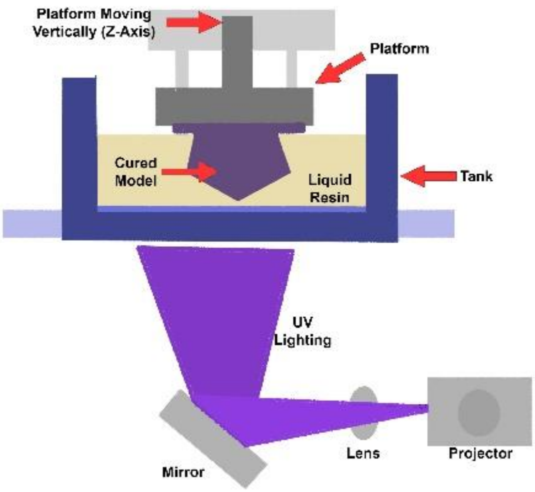


FIGURE 6. **SLA Method**

The SLA approach yielded a layer thickness of 0.05–0.10 mm. Complex things with intricate details and realistic shapes can be produced with the SLA printing technology. [32]. The printer utilized in the SLA process is the Phrozen Sonic Mighty 4K. The specifications of this printer are described in the Table 3.

TABLE 3
Specifications of the Phrozen Sonic Mighty 4K Printer[42]

Item	Specifications
System	Phrozen OS
Technology	Resin 3D Printer - LCD Type
LCD Specification	9.3" 4K Mono LCD
Light Source	405nm ParaLED Matrix 2.0
Release Film	FEP Film
XY Resolution	52 µm
Layer Thickness	0.01-0.30mm
Maximum Speed Print	80mm/ hour
Power Requirement	DC 24V ; 3A
Printer Size	29.3 x 29.3 x 43.2 cm
Print Volume	20 x 12.5 x 22 cm

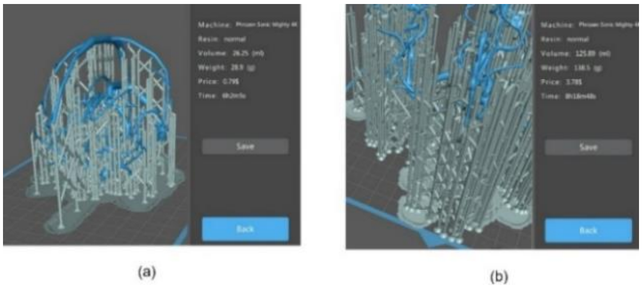


FIGURE 7. **Pre-processing SLA Method (a) Venous Blood Vessels (b) Arterial Blood Vessels**

The first step in the SLA printing process is to provide supports to the object's structure. This addition lessens the possibility of harm occurring during printing. The SLA approach with Chitubox software was used to provide support in **FIGURE 7.**

III. RESULT

A. 3D MODEL RESULT

The first step in the 3D segmentation process is the application of the threshold method. Compared with the manual method, the threshold method offers significant efficiency. In this case, the threshold method can reduce the working time by about 30 minutes compared with the manual method. In addition, the threshold method is relatively easy for users to understand and learn and uses a pixel separation technique based on brightness values to distinguish between target organs and background, thereby simplifying the complex organ tissue segmentation process. Manual segmentation takes about 45 minutes per patient and faces greater challenges. Users must have a deep understanding of the structure of the organ to be segmented, which increases the complexity of the process. The manual method is often prone to errors and produces unclean segmentation, especially in areas with fine details, such as small blood vessels. However, the manual method is still used, especially when the segmentation results from the threshold method are inadequate. In this case, users can complete the segmentation with manual marking (manual painting) to fill in areas that are not detected by the automatic program. **FIGURE 8**. shows the results of 3D model construction in both arteries and veins.

The urgency of sacral pre-learning in practice using cadaver simulation involves expensive infrastructure, ethical and legal issues, and animal models. Training models need to be designed with efficient training goals, namely physical models, 3-D printing, and simulators. Simulation models with virtual and augmented reality have been shown to reduce the time of practitioners with experience in laparoscopy, with an estimated reduction of 30 to 58% [43].

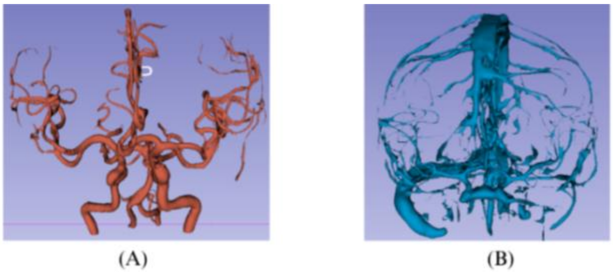


FIGURE 8. Result Blood Vessel (a) Artery (b) Veins

The crucial step in the small vessel distribution pattern in DICOM varies between different subjects, making direct comparison of small cerebral vessels at the voxel level a difficult task [44]. The imaging resolution varies between veins (256 x 256 voxels) and arteries (512 x 512 voxels), with the higher resolution in arteries allowing for more detailed identification of structures. This difference in voxel size greatly affects the accuracy of segmentation results in both types of vessels, requiring a segmentation approach tailored to their characteristics. The segmentation and labeling process involves careful manual marking, with arteries marked in red and veins in blue in the 3D model.

To maintain the highest standards of accuracy, the labeling process in FIGURE 9. is adjusted to trusted anatomical references, such as "Essential Clinical Anatomy" [45]. In addition, validation by expert clinicians is also required to ensure the accuracy of the results. The combination of the use of sophisticated software tools, comprehensive anatomical references, and expert validation. The 3D models of cerebral vessels produced from this process have a high level of detail and accuracy. This has the potential to have a significant impact in various medical fields. Such as improving the quality of medical education, surgical planning, and research in neurovascular studies.

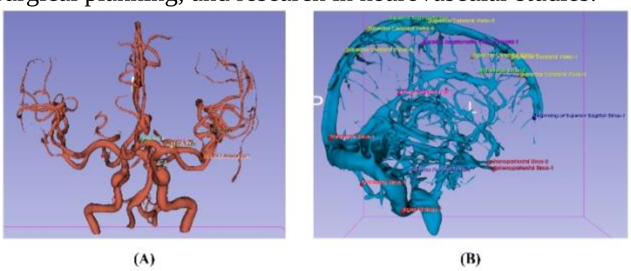


FIGURE 9. Labelling Blood Vessel (a) Artery (b) Veins

FIGURE 10 presents a valuable image for surgical planning[46]. In the left section of the image (views A, B, C), the skull is presented in a solid state, emphasizing the external face characteristics. Meanwhile, the right side of the image shows the skull in transparent mode, providing a clear visualization of the organs inside the skull. This visualization method provides surgeons the opportunity to study the interaction between bone structures and soft tissues in greater depth, which is crucial in complex surgical procedures.

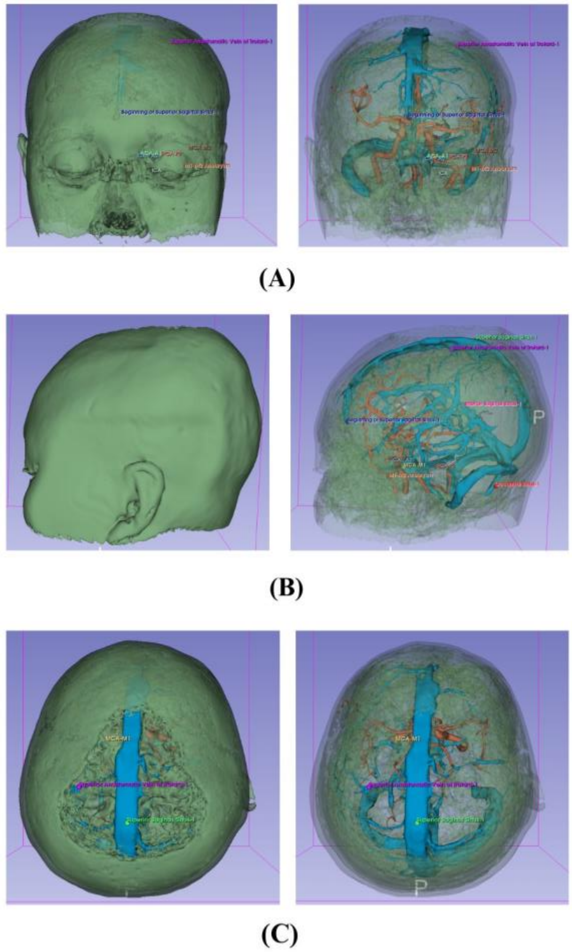


FIGURE 10 Surgical Planning 3D slicer (A) Front View (B) Side View (C)Top View

B. 3D PRINTING RESULT

Post-processing involves removing supports in both methods. SLA resin models are purified with isopropyl alcohol to remove resin residue, then cured with UV light to solidify the resulting resin. FDM models are often printed using supports especially on difficult 3D model surfaces [47].

FIGURE 11. depicts the results from 3D printing using fused deposit modeling (FDM) method. Grid, top surface pattern monotonic line, bottom surface pattern monotonic, and internal solid infill pattern rectilinear, nozzle at bamboo lab 0.4 mm. The printing of the artery in the middle section of FIGURE 11. (a) took 58 minutes and 12 seconds, and the filament required was 18.68 g. The printing of artery 1 on the left side of FIGURE 11. (b) took 1 hour, 4 minutes, and 12 seconds, and the filament required was 16.74g. The printing of artery 2 on the right side of FIGURE 11. (c) took 2 hours and 54 minutes, and the filament required was 51.11 g.

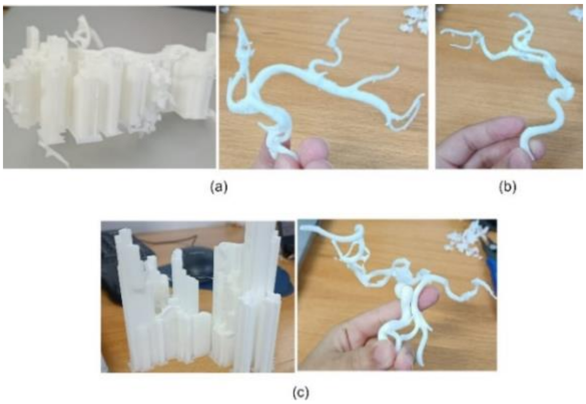


FIGURE 11 FDM Printing Method's Procedure and Outcomes (a) Arterial Blood Vessel Part 3 Center (b) Arterial Blood Vessel Part 1 Left (c) Arterial Blood Vessel Part 2 Right

FIGURE 12. delivers the results from 3D printing using stereolithography apparatus (SLA) method. Printing of venous blood vessels FIGURE 12. (a) using the SLA method for venous blood vessels from open source. Printing time is 6 hours, 2 minutes, and 5 seconds with automatic support. The volume of resin needed is 25.25 mL and the weight is 28.9 g. The printing of the venous blood vessel in FIGURE 12. (b) used the SLA method with DICOM data source at a scale size of 100%. The resin printing time is 8 hours, 18 minutes, and 48 seconds using automatic support. The volume of resin required is 125.89 mL and the weight is 138.5 g.

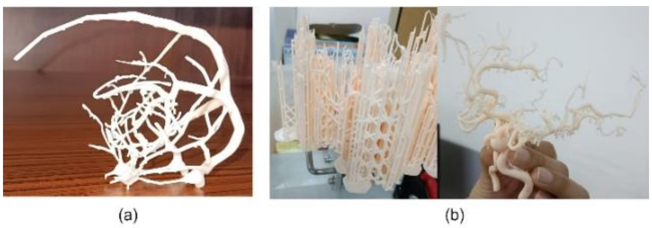


FIGURE 12 SLA Printing Method (a) Venous Blood Vessels (b) Arterial Blood Vessels

Table 4 shows a comparison of the two approaches. A minimum printing layer thickness of 10 µm is required for the FDM process. While commercial SLA printers can easily reach more detail down to 25 µm per layer without worrying about nozzle blockage, most desktop FDM printers are only able to achieve a thickness of 100 µm[48]. SLA can print parts with high resolution as small as 10 µm, but FDM can only produce components with higher resolution as large as 40 µm.

TABLE 4
Comparison of FDM and SLA Printing [42]

No	Material	Tool	Time	Advantages
1.	Filamen	Bamboo X-1 Carbon	4 hours 56 minutes 24 seconds	Solid object.
2.	Resin	Phrozen OS	8 hours 18 minutes 48 seconds	The printing of intricate lumens can be shaped well and in detail. Easily removable support.

Considering that the 3D printing industry is growing exponentially and continues to provide improved 3D printer models, the print resolution values should only be used as a comparative guideline[49].

TABLE 5
Comparison of accuracy validation [50]

Object	References	3D Model	3D Printing
The right vertebral artery	2.78mm-3.61mm	5.574 mm	5.722 mm
The left vertebral artery	3.12mm-3.69mm	4.221 mm	4.21 mm

The anatomical structure of the cerebral blood vessels in humans can vary in shape, size, and path in each individual. Factors that affect the size of blood vessels include age, genetics, blood pressure, metabolic health, and physiological conditions. In TABLE 5, vascular segmentation accuracy is evaluated by comparing the vessel radius and centerline path between the generated segmentation model and the ground truth model [51]. Given the complexity of the medical image acquisition process, direct validation of 3D models is often impractical. Therefore, the comparison method of results becomes an effective alternative for validation. The analysis can be focused on measuring the diameter of blood vessels at specific points, which allows the evaluation of cross-sections perpendicular to the blood vessel path [52]. This approach not only facilitates the assessment of vascular morphology accuracy but also allows the detection of anomalies or stenosis that may not be identified in conventional 2D analysis.

IV. DISCUSSION

To interpret the results, the segmentation performed through thresholding effectively visualizes the 3D model, followed by 3D printing. The 3D model serves to display small blood vessel parts that are located in areas difficult to detect with the naked eye. With the help of software, such as 3D Slicer, the model can be accessed and rotated 360 degrees to gain a comprehensive view from every angle. With this model, the doctors can observe the branches of blood vessels and use them as a guide during surgery. The validation process of the branches of blood vessels is also carried out to ensure that all structures correspond with the medical images produced from the initial segmentation. Furthermore, these image modelling results are then emphasized using 3D printing. The results of SLA printing are more similar to the desired anatomy, making it suitable for medical applications that require high precision and accuracy. The function of the vertebral arteries in supplying blood to the brainstem, cerebellum, and posterior regions of the brain makes the validation measurements of the left and right vertebral arteries very urgent. The anatomical variations of the vertebral arteries (VA) have significant implications for neurosurgery and forensic pathology. Medical intervention planning requires a diagnosis because disturbances in blood flow between the right and left vertebrae can indicate blockages that affect blood supply to the brain [53], [54].

In this study, we also validate the results. FIGURE 13. shows all validation made in this study. Validation of measurements made at the left and right vertebral artery sites using a caliper and 3D Slicer: the caliper measurement is 0.421 cm, and the validation measurement for FIGURE 13. (a) of the left artery on 3D Slicer is 4.221 mm, translated to 0.4221 cm. The caliper measurement is 0.5722 cm, and the measurement for the right artery in FIGURE 13. (b) on 3D Slicer is 5.574 mm converted to 0.5574 cm.

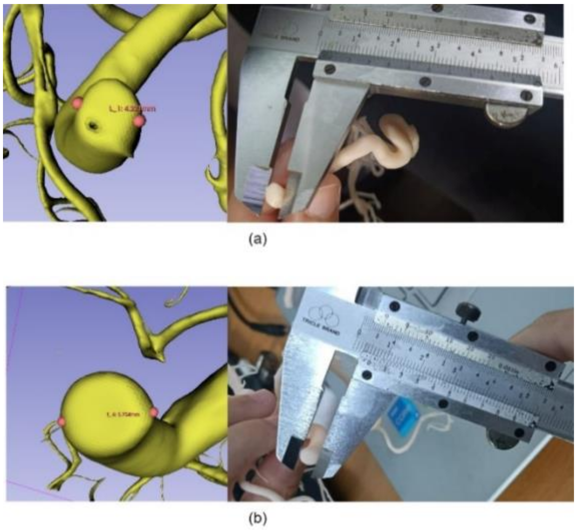
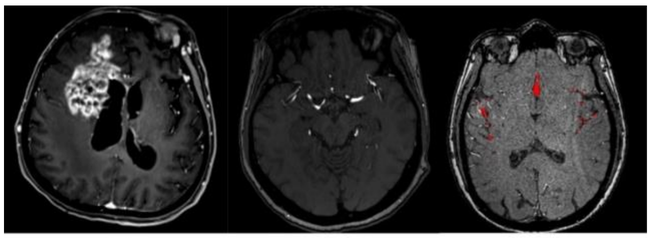


FIGURE 13 Measurement validation for (a) the left vertebral artery and (b) the right vertebral artery

Samaer Zamy Alsofy et al. suggest that the use of 3D models in virtual reality (VR) can improve surgical outcomes[55]. However, our research shows that similar results can be achieved without the need for VR tools. This software provides flexibility such as zooming in and out, displaying objects from a 360° perspective, and adding labels to the observed organs. This research not only offers convenience in visualizing anatomy but also efficiency in the medical observation process without the need for additional equipment like VR. Xiaomei Zhao et al., in their original data paper, reported the longest training time among all the approaches reviewed, which took about 12 days to train the model [56]. Meanwhile, the method we used, which is segmentation with the Thresholding technique, shows much higher efficiency, with a training time of only about 30 minutes.

The absence of integration within the clinical setting constitutes a major obstacle to the effective application of machine learning image reconstruction in MRI. Currently, reconstructions are performed offline and are not easily accessible to clinicians [38]. The process of reconstructing TOF-MRA images using iterative reconstruction algorithms can also be considered for image noise reduction [39]. In comparison with our experiment, we used MRA data set reconstruction so that it could be modeled in three dimensions, while TOF images do not have volume and can only be visualized in two dimensions. By updating our results, the three-dimensional model can be labeled on the anatomy of blood vessels and used as a phantom tool to assist doctors in training.

In this study, we find some weaknesses. The quantity of mistakes that arise during the development process—radiological imaging, image segmentation, STL file conversion, STL post-processing, pre-processing for 3D printing, and post-processing—affects the correctness of 3D anatomical models. These steps all rely significantly on tools, software, and human error. Before printing, it is necessary to prepare the patient's 3D model data so that it can be converted into machine code that can be read by the SLA printer. Software like Chitubox 1.9.0 is used to provide support during the printing phase. This software adds support structures to the 3D model to ensure precise and stable printing results throughout the entire printing process.
Image Acquisition, 3D Model Reconstruction and 3D Printing with a focus on the object of veins and arteries in the brain can be a planning for surgical steps, identify potential problems before the procedure begins, and develop a more precise approach. By using a comparison of 3D printing methods FDM and SLA, with the results of measurement validation and visualization close to the original anatomy.



(a) (b) (c)

FIGURE 14 (a) Dicom Data for Sick Cases, (b) Dicom Data for Normal Cases, (c) Comparison of Normal Arteruil Reference DICOM Data

From the quantitative comparison of the sick data shown in FIGURE 14 (a) and the average data in FIGURE 14 (b) used for 3D modeling, the sick tumor part case is used in surgical training. Compared to the reference Valderrama N [57]. FIGURE 14 (c), which uses normal artery DICOM cases, the presence of diseased artery cases can lead to improvements in surgical training. The vascular model validator will be validated by radiology parties. Radiology validators focus on the specific evaluation of images and brain vascular models to ensure they accurately reflect the features of the original shape. 3D Printing Result Post-processing involves removing supports in both methods. SLA resin models are purified with isopropyl alcohol to remove resin residue, then cured with UV light to solidify the resulting resin. FDM models are often printed using supports especially on difficult 3D model surfaces.

The difference from the previous research results in the Encarnacion study, Manuel et al., is the combination of planning and design of intraventricular markers; the study has yet to develop a model for specific cases such as brain tumors. This paper has a 3D model of a brain tumor case and more detailed image preprocessing. Compared to the previous paper, which was used once, the 3D model used in the paper can be used repeatedly.

The study's implications are improving the quality of surgical training by providing realistic simulations and 3D printing models for surgeons as pre-operative planning before surgery on actual patients. Second, it can reduce the risk of errors during complex operations, especially in sensitive areas such as the brain. The study's limitations are that it still uses semi-automatic segmentation, so the reference for future research directions requires more indepth automatic image processing segmentation. With the results of 3D Printing, it can be developed using more realistic materials to support each wall of blood vessel tissue with the aim of pre-operative planning that has a more accurate sensation.

V. CONCLUSION

This paper aims to enhance the visualization of 3D brain blood vessel models for neurosurgeons. The primary objectives are to improve surgical outcomes, reduce operation time, minimize procedural errors, and accelerate patient recovery. By utilizing 3D Slicer technology, doctors can obtain a clearer view of brain vascular structures. Although reconstruction can be performed automatically, manual intervention is still required to refine undetected areas. Validation can be performed by comparing blood vessels and calculating cross-sections perpendicular to the vessel path. For future research, it is recommended to develop more advanced automatic segmentation methods, particularly for blood vessels.

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