Creation of Additive Manufacturing Models of Intracranial Aneurysms

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Abstract

Intracranial aneurysm is a condition in which weakening of the blood vessel wall in the brain, along with the pressure of blood flow, results in a protrusion from the vessel wall that becomes filled with blood. This condition may result in a rupture which is often fatal or has other serious repercussions. This research focuses on creating patient-specific three-dimensional models of the inner lumen of aneurysms with their connected significant vasculature. Three sets of anonymized head and neck computed tomography angiography (CTA) scans were obtained and were put into the correct stack sequence using a program script. Image processing software was then used to convert the areas of interest in the stacks of CT scan images into three-dimensional renderings of aneurysms with a STL file format. Additional image processing software was used to further refine and smooth models. The models were fabricated using additive manufacturing. These models could be used for the education of patients in order to increase compliance for surgical procedures to prevent aneurysm rupture and to increase trust with their physicians. The models could also be used by physicians to understand the geometry of their patients’ aneurysms, which would potentially inform their treatment strategy.

Keywords: intracranial, cerebral, aneurysm, patient education, additive manufacturing

Introduction

An aneurysm is a condition in which a blood vessel wall becomes weakened and forms a protrusion due to a defect of a structural protein – collagen – in the wall and the repetitive pressure of blood flow. Aneurysms within an artery are dangerous because they are under high pressure from receiving the ejection of blood from the heart and may rupture. Ruptured cerebral aneurysms are fatal in 40% of cases, and 66% of survivors suffer a permanent disability. Six million people in the United States currently have an unruptured brain aneurysm, and each year about 30,000 people have a cerebral aneurysm rupture.¹

Aneurysms most commonly occur in a connection of blood vessels at the base of the brain called the Circle of Willis. About 90% of aneurysms form in the anterior circulation and about 10% form in the posterior circulation.² It has been estimated that about 50% of the population have arteries that are absent or underdeveloped in the Circle
of Willis. There is a correlation between Circle of Willis variation and intracranial aneurysms, and it is thought that the variations have a role in the formation of aneurysms.

Most unruptured aneurysms do not present any symptoms and are discovered incidentally. The initial examination of choice for acute intracranial aneurysms is a computed tomography (CT) scan, upon which blood appears whiter than the surrounding tissue and usually allows for detection of a cerebral aneurysm. More in-depth imaging used for the evaluation of treatment options for a cerebral aneurysm includes computed tomography angiography (CTA), magnetic resonance angiography (MRA), and intra-arterial digital subtraction angiography. CTA involves taking a series of x-rays after the patient has been injected with a contrast material. MRA involves using strong magnetic fields to create an image after the patient has been injected with a contrast material and usually takes between a half-hour to an hour longer than CTA. Intra-arterial digital subtraction angiography (IADSA) uses a catheter, x-rays, and contrast material. It is considered to be the “gold standard,” but because of its invasive nature and high costs, it is used less often than the other two methods.

There are three different treatment options that can be followed for a patient who has an intracranial aneurysm. The first option is to monitor the aneurysm over time to observe its growth. For smaller aneurysms, the risk to the patient from surgical procedure may be higher than that of the aneurysm rupturing, which is why this method may be a good option for many patients. The other options involve surgical intervention. The most common treatment to prevent aneurysms from rupturing is an endovascular treatment. In this method, a catheter is inserted in a femoral artery and is guided to the site of the aneurysm. The catheter then releases soft platinum coils into the site of the aneurysm, which promote blood clotting and occlude the aneurysm. However, this method cannot be used for all cases, such as when the aneurysm is too large, has too large of a neck, or the blood vessels of the patient are too twisted to navigate safely. An older method which has a higher risk of complications, but that covers cases for which endovascular treatment is inappropriate, is surgical clipping. A craniotomy is performed to allow the surgeon access to the vasculature and permanent metal clips are applied to the neck of the aneurysm in order to block it from the blood stream.

There have been additive manufacturing models of intracranial aneurysms made in the past in order to aid physicians with presurgical simulation, navigation of the aneurysm during surgery, and junior surgeon training. These models include brittle, solid models and elastic, hollow models. Studies found that the physician and junior surgeon response was mostly positive but in a few cases the surgeons encountered obstacles such as hard artery walls, vessels adhered to each other, or clots within the aneurysm that could not be predicted through use of the three-dimensional models.

However, research has not focused on models made specifically for patient education and procedure compliance, which is the focus of this research. The hypothesis was that CTA scan data, which is already commonly used for evaluation of patient aneurysms, could be used to generate an additive manufacturing model of patient-specific intracranial aneurysms that could be used to educate the patient on their particular aneurysm and the treatment they are undergoing. These models could also be used by the physician to consult when forming a treatment plan for their patient.

Methodology

Following a protocol approved by the Institutional Review Board of the Milwaukee School of Engineering, three anonymized sets of CTA scan images in DICOM (Digital Imaging and Communications in Medicine) format were obtained from the Department of Radiology at the University of Virginia. The slice thickness of the the scans were 0.625 mm. The images had filenames with numbers that were not sequential, so a MATLAB (MathWorks) program was created in order to sort and rename the stack images in numerical order based off of information extracted from the header of each file.

The images were evaluated using the open-source software Image J. In this software, basic 3D renderings were created in order to view the aneurysms, as shown in Figure 1. It was determined that two of the three sets of scans were appropriate for the further creation of models. These sets of scans were referred to as Anon-1 and Anon-2.
Anon-1 was a case presenting a basilar tip saccular aneurysm. Anon-2 was a case presenting a saccular aneurysm located in the cavernous portion of the right carotid artery and a fusiform aneurysm located in the middle cerebral artery.

Figure 1. A: 3D rendering of a CTA scan stack without any image processing. B: 3D rendering of a CTA scan stack after painting away of the upper skull and contrast enhancement.

The scan images were imported into Mimics (Materialise NV) software using the “force raw import” option and by indicating values of height, width, and pixel spacing that were previously read from the DICOM header. Low byte first and unsigned short pixel settings were chosen. Using thresholding of greyscale values, a mask was created of the skull and vasculature and a different mask was created of only the skull. A Boolean operation was used to subtract the mask of the skull from the mask of the skull and the vasculature. Region growing was then used to select only the material of the aneurysm and vasculature using seed points in order to reduce the amount of image artifacts. The models after region growing are shown in Figure 2A and Figure 2B. After this, the volume rendering was manually edited slice-by-slice using add and delete drawing tools in order to refine the mask further. The models after manual editing are shown in Figure 2C and Figure 2D. Finally, the models were exported as STL (stereolithography) files.
The STL files were imported into Freeform Modeling Plus (Geomagic) software. Layers of clay were added to the models and then the areas were smoothed. Knife and smudge tools were used to separate areas that became stuck together during smoothing. After smoothing of the entire geometry, areas for smoothing were selected in a way to minimize the amount of volume loss from the smoothing process. The refinement process is shown in Figure 3. Finished models were then exported as STL files.
Support structures were made in Freeform software to connect the separate pieces of vasculature in the Anon-1 model. There were two separate pieces to Anon-1’s vasculature because the patient either did not have fully formed posterior communicating arteries present or because they did not appear on the CTA scan due to factors such as timing of contrast material and stenosis.

The models were manufactured using PA 614-GS (40% glass filled nylon 12 laser sintering material) and SLS (selective laser sintering). The SLS printer model used was the Sinterstation 2500 Plus, which was manufactured by 3D systems and used a CO₂ laser.

Support structures in the Anon-1 model were colored black in order to better differentiate them from the vasculature.

**Results**

Models were successfully fabricated and obtained. Models were visually validated by Dr. Wintermark for accuracy. Images of the models can be seen in Figure 4.
In this study, there was no interaction between the models created and their patients. In order to test the effectiveness of these models, the best environment for further studies to take place would be one with radiologists, technicians, surgeons, and patients all working together.

Different parameters and techniques for creating and presenting the models could be varied. The models and presentation techniques the patients preferred could be measured using surveys where the models were rated based on different criteria.
In this way, a set of standard practices for the creation of 3D models of aneurysms through additive manufacturing could be developed based on which procedures are found to produce models that the patients view as highest quality in enhancement to their learning.

In this study, a multi-step protocol was developed to successfully convert CTA images of aneurysms to physical 3D models. In order for the protocol to work accurately, there must be a large quantity of scan slices with a section thickness as thin as possible. In cases where an aneurysm is small relative to the vasculature it is present on, it may be difficult to obtain a useful model due to potential volume loss through the removal of image artifacts and the smoothing process.

The main way in which these 3D, physical models may be useful for patients would be in helping them to appreciate the size of their aneurysm as well as the size and complexity of the surrounding vasculature. A physical model has advantages to learning over a computer rendering, which is a 2D image that creates the illusion of 3D using perspective. Viewing a physical model allows a patient to use the natural method of binocular vision to gain three-dimensional information. It also allows patients to integrate other sensory information, such as touch, to enhance their learning. A patient having better understanding of the size of their aneurysm relative to the normal vasculature surrounding it may lead to increased compliance for surgical intervention.

The models created in this study could also be used as a type of mold on which negatives could be created. Negatives could be made of a material that more closely resembles the material properties of vasculature and could be used for surgical planning and practice of surgical procedures.

Future work includes computation fluid dynamics (CFD) analysis of the models. The STL files created during this research could be either imported directly to CFD software packages or could be imported first into other software for remeshing or exportation as a solid geometry file type. The main benefit of CFD would be to characterize the mechanics of aneurysms, especially if fluid-solid interactions were included in the model. If these types of interactions were better understood, then patient specific CFD might be used as a tool to help physicians make treatment decisions.

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