MODEL FOR PRE-SURGICAL INTRACEREBRAL HEMORRHAGE PLANNING

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Abstract—Intracerebral hemorrhaging can affect any individual at any age, but is most prevalent for individuals who are at high risk of strokes and seizures. This condition is dangerous as it causes blood clotting and could lead to a stroke. For this reason, the client has tasked the team to come up with a phantom head model that can be scanned into an MRI, so a neurologist can practice different surgical techniques. These include stereotactic clot aspiration and craniotomy. Stereotactic clot aspiration is a minimally invasive surgery for large clots and involves catheter removal. This method is also known as irrigation [1]. Another commonly used method is craniotomy which involves cutting a hole in the skull with a drill to expose the brain and remove the clot [2]. For this reason, the team has decided to come up with a phantom model that will allow the neurosurgeon to use a catheter and drill to remove said blood clot. Once the team developed the phantom, it was found that there was an apparent difference between the contrast of the DICOM images of the non-clot and clot skull models and a difference in the calculated and actual volume of the capsule that contained the clotting swine blood. Overall, from these results it was found that the team's phantom model was correct in displaying the hemorrhage, but still needed a more visible capsule, more access points for the neurosurgeon to look into during the surgery and models with different locations for the hemorrhage. In addition, a focus of this semester was on designing a clot that was self-healing, so it could handle multiple puncture sites from syringes and catheters without draining the clotting blood within it. The team did research into this topic and was able to find a silicone self healing capsule that could be placed within the MRI without causing any severe artifact issue. With that in mind, the team took three different sets of scans with the new capsule design, one set with just a capsule without the coagulated blood, one with the coagulated blood and one with the catheter puncturing the capsule, or wound site. It was found that the images displayed SNR values that showed a significant difference between values that would not show any difference and with that in mind the team found the entire design could be used to display accurate image modeling of an intracerebral hemorrhage.

INTRODUCTION

Our project works with intracerebral hemorrhaging (ICH). ICH affects between 40,000 and 67,000 Americans each year with an expected 10 year survival rate of 24.1% [3]. Clots can form because of ICH. These clots form when a blood vessel bursts, releasing blood into the brain [4]. This results in the arteries near the clot lacking oxygen-rich blood, causing the patient to

experience strokes [5]. Thus, immediate action must be taken for ICH patients since blood shears white matter, resulting in brain damage. Over time, the RBCs from the blood released in the bursting of the vessel coagulate and separate from the plasma. This separation makes individual clots highly heterogeneous which complicates the decision of which method of evacuation to utilize, since the best method is dependent on the stiffness of the clot [6]. Currently, it is difficult for surgeons to assess the stiffness of clots prior to surgery. When a patient displays symptoms of ICH, it is standard for that patient to undergo diagnostic tests such as an MRI and a CT scan. These tests allow doctors to determine the location of the clot, but do not provide information regarding the stiffness of the clot [4]. Without knowing the characteristics of clots, it is difficult for neurosurgeons to decide on a surgical approach prior to surgery.

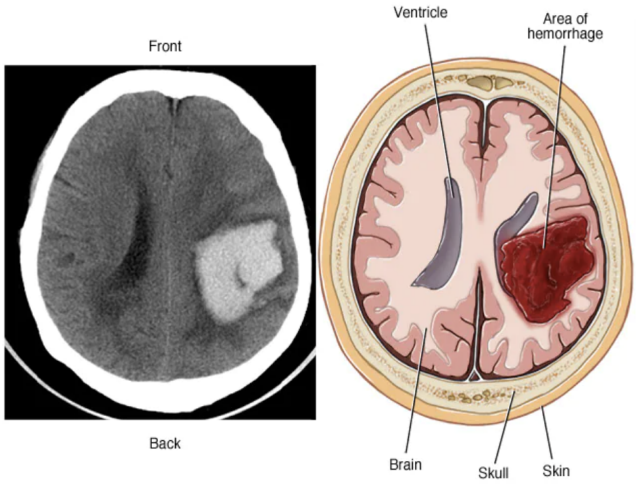

Figure 1. Intracerebral Brain Hemorrhage[7]

Hypertension and old age both increase a person's risk of experiencing ICH. Even though ICH is common, doctors are unable to stabilize patients that come into the hospital with ICH. Now, multiple surgical methods have been developed which allow doctors to evacuate clots before brain damage occurs. Removal of the clot is critical as clots can cause cells in the brain to self-destruct and act as harmful biological cues in the brain[5].

When considering the removal of a clot, its mechanical characteristics must first be considered. Two different types of clots are commonly identified in ICH patients. One type is a fluid or gel-like, for which the best removal method is irrigation or suction, performed by a vacuum catheter. The second type of clot is much stiffer and requires a drug-based approach. The drugs break down the clot before it is evacuated, and once the clot becomes less viscous, surgeons can remove it with a vacuum catheter.

A medical phantom is a device that is used to calibrate imaging devices and to develop methods to better analyze images. Phantoms often seek to mimic the material characteristics of human tissue. Researchers are able to manipulate and analyze phantoms with greater ease than they are able to manipulate human tissue due to ethical reasons and some secondary characteristics. This allows the imaging machinery's resolution and accuracy to be tested and calibrated [7].

When the interface is imaged using MR elastography (MRE), it will show how different

stiffnesses appear on MRI. The gel to gel interface is meant to mimic the interface between clots and native brain tissue. Currently, there are no phantoms that mimic clot-tissue interactions in a gel to gel interface, however other phantoms have been designed that analyze the appearances of different stiffnesses on various diagnostic images. For example, researchers from Switzerland designed an anatomically correct phantom that modeled white matter and gray matter[8]. They were able to mimic the material properties of these tissues using agar gel.

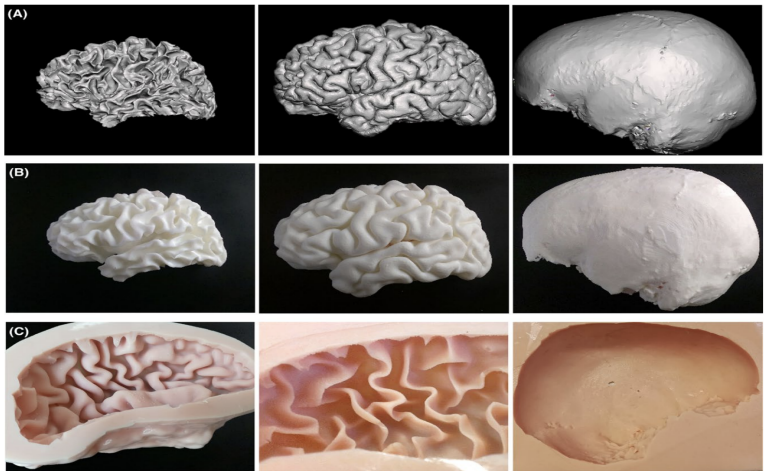

Figure 2. Switzerland Agar Gel Model[8].

Other phantoms have explored the idea of gel interfaces, involving hydrophobic sprays and wax barriers [9]. These come with their own downsides, such as stability issues or a lack of anatomical detail. This phantom uniquely provides a long-lasting, anatomically relevant model for the gel-gel interface, which differs in its mechanical properties compared to other phantoms and can be verified via rheology.

The previous UW- Madison Team that came up with the polyacrylamide (PA) gel model for the phantom. Results obtained from rheometric analysis were quite promising, as the team was able to develop PA gels that closely mimic brain tissue and its mechanical properties. Results from the MRI scan of the newly designed sample holder were also promising. By fabricating the holder in the shape of a human skull, the team fit was able to place the phantom snugly into the MRI head pillow, thus removing space between the pillow and holder, and ultimately minimizing phase issues found in the previous design.

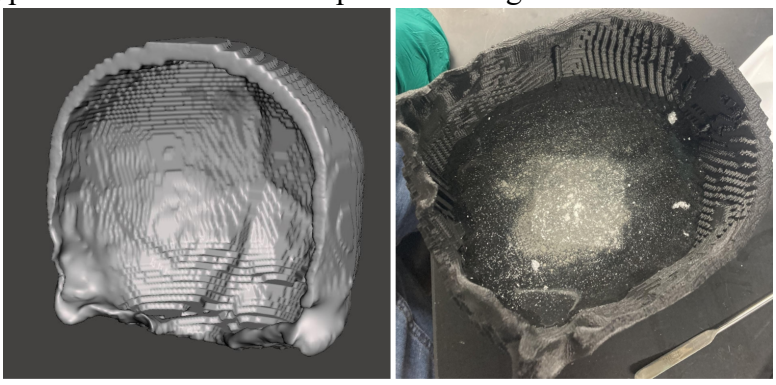

Figure 3. UW-Madison team model

Currently, it is difficult for surgeons to assess the stiffness of clots prior to surgery. When a patient displays symptoms of ICH, it is standard for that patient to undergo diagnostic tests such as magnetic resonance imaging (MRI) or computed tomography (CT) scans, which allow doctors to determine the location of the clot, but do not provide enough information about the stiffness[4]. The phantom model would act as a model for surgeons to practice their surgical procedures. Ideally, surgeons will be able to compare the images of their patients to those of the phantom and deduce the best method of clot extraction. The goal of the project was to create a phantom model that would simulate the interior of the brain and have variable sized clots that could be imaged to validate the neurosurgeons effectiveness at mapping techniques on an anatomically correct phantom model. The team would also focus on improving the phantom model so the hemorrhage within the model would be accurately seen and removed from the first CT or MRI scan. Additionally, the phantom model would contain several access points to place the catheter and swine clotted blood, simulating the hemorrhage, thus allowing for optimal practice for the removal of the clot.

A brain phantom is used by neurosurgeons to compare the MR scans of the phantom with a scan of their patients' brains. The phantom's purpose is to illustrate the stiffness of the patient's brain [10]. Characteristics of the patient's brain that are compared to the phantom include the rigidity, structure, clots, and fluids. It is essential for the phantom to have a precise replication of the brain's components, since its design will help physicians decide how they will treat the patient. For instance, when doctors begin to remove a blood clot from a patient they must decide between using a catheter or creating an incision [11]. Thus, it is very important for brain phantoms to represent the human brain closely.

The composition of the phantom is therefore the most important part of the design and fabrication. This focus thus leads to the research of different biomaterials to make up the phantom model. The other main focus regarding improvements to the model is adding more features to the phantom to increase its anatomical accuracy. This includes the incorporation of air and fluid pockets to mimic sinuses and CSF, respectively. Progress has been made with respect to this design advancement as the team was able to create a 3D replication of a child's skull from a sample CT scan via 3DSlicer and Mesh mixer 3D, allowing the result to printed using a 3D printer and PLA.

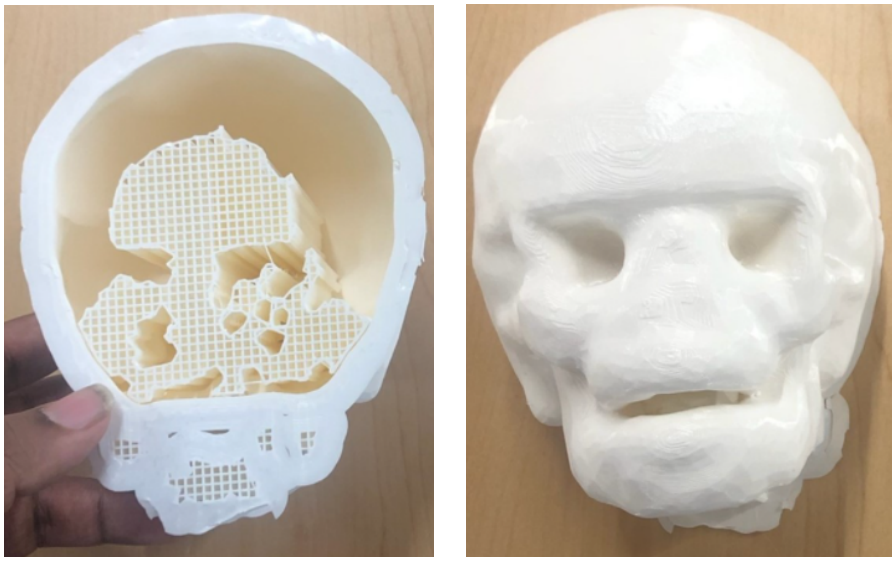

Figure 4. 3D printed skull model

In order to ensure that the final product meets the requirements of Dr. Block, the team generated a document of design specifications, which include all of the properties that the final design must adhere to. The document describes the physical and operational characteristics of the skull model, the steps that will be required to produce the model, as well as documentation of previous designs of how the teams used these designs as inspiration and models for this product. The design specifications are the following, overall the skull model will be 3D printed and made of PLA to allow for the most practical material that can be scanned within an MRI. The model must contain a pocket able to contain up to 25mL for the sample hemorrhage. The Phantom model's total volume must be no larger than 1500cc and no smaller than 100cc. Additionally, the anatomical features of the skull must accurately represent a head with the possibility to contain air and fluid components that will be cut from the gel. Spatially, the skull model must be accurate enough to allow for separate regions of the brain to be recognizable. Also, there will be an in depth fabrication process, so the following procedures can be replicated for affordable commercial purposes. Lastly, the model must be enclosed in a way that there will exist a way for the neurosurgeon to change the internal skull pressures to match the conditions of a specific hemorrhage or blood vessel pathway.

METHODOLOGY

The full skull pressurized model will be entirely pressurized by using internal gas chambers that will act as the blood vessels and hold oxygen/hydrogen gas. Depending on the conditions the neurosurgeon wants to work on with the brain, the skull will act in accordance with those specified pressure conditions. The pressure will increase by having the volume of the gas fill the chamber of the skull, while a reduction of pressure will occur by having pressurized gas leave the chamber. Due to this pressurized system, this skull model will be able to most accurately act as an actual brain model. However, this model will require complex hardware to set up the pressurized chamber and will need to be placed in a location where it will not have any interaction with the polyacrylamide gel so as to not cause any combustible reaction.

Additionally, due to this complexity the idea of having this skull model be available commercially reproducible will no longer be applicable.

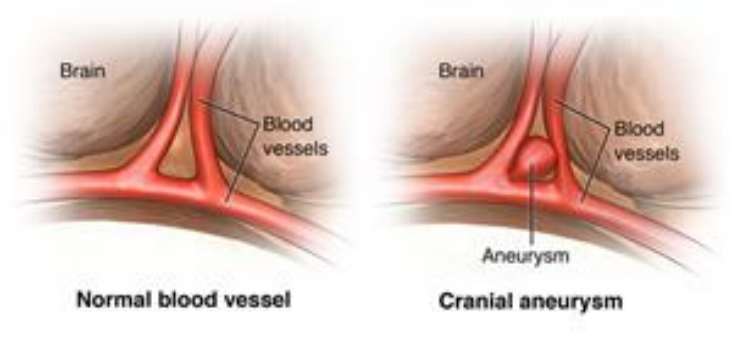

Figure 5. Pressurized System [12]

Similar to the last design, this nonpressurized skull model will be a full model as it will not be cut laterally across the brainstem, but will illustrate the entire brain including all the accessory lobes. However, the model will not be pressurized and will not be able to accurately change the corresponding blood vessel pressures to compare to an actual skull model. Due to this hardware change, the complexity of the model will be simpler, but will still require more time in Slicer3D for the processing of the skull. In the future, this model will allow a pressurized system to be added more easily than the half, so that it can be converted into a different design. One drawback with this model is that it will be more difficult for the neurosurgeon to practice certain surgical practices as it will require more robust methods to reach certain difficult regions in the brain as compared to the half model.

Figure 6. Full Skull [13]

Unlike the previous designs, the half skull model will no longer have a full scale figure and will now be cut laterally across the brainstem to allow for only the most apparent lobes that a neurosurgeon to work with. Though this model is the least accurate to an actual human model, this model would work the best for the neurosurgeon practicing to perform a surgical procedure as it will allow the easiest and best access to all the parts that are necessary to be worked on. However, this skull will not be able to be made into a pressurized system, as the blood vessels transporting the blood will be taken away from the skull and will not adhere to the actual biomimicry of an actual adult skull. Lastly, this

model will be the easiest to be made in 3DSlicer as it requires the least amount of time to process.

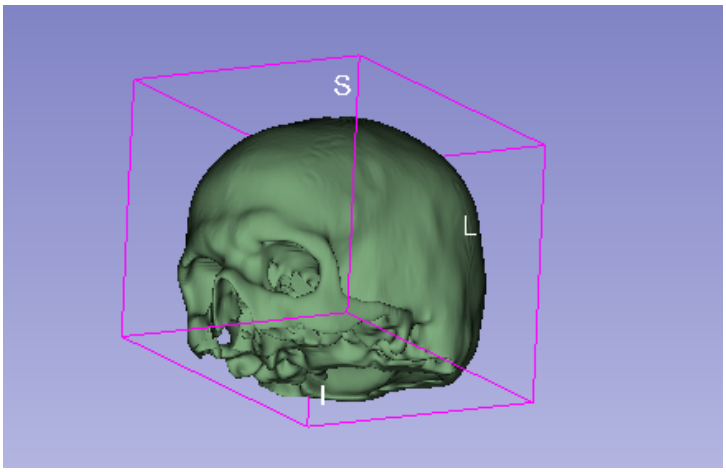

Figure 7. Half Skull

Table 1: The Pre-Surgical Hemorrhage Model design matrix.

Critera	**Weight**	Full Skull Pressurized		Full Skull Non-Pressurized		Half Skull	
Ease of Fabrication	30	1/5	6	3/5	18	4/5	24
Bio-mimicry	25	5/5	25	4/5	20	2/5	10
Durability	20	2/5	8	3/5	12	3/5	12
Replicability	15	1/5	3	3/5	9	4/5	12
Cost	5	1/5	1	3/5	3	4/5	4
Saftey	5	5/5	5	5/5	5	5/5	5
Total	100	**48**		**67**		**67**	

This criteria would include how feasible it would be for the team to create the phantom model and set it up for simulation. The team weighted this category the highest due to it being overall the most important factor in the project to be successful. We factored in the ease of creating the skull model and adding the non homogenous aspects of the model such as the hemorrhage (clot) and air pockets. The Half-Skull model won in this category since the model is open. The openness of the Half-Skull allows the team to create the non homogenous aspects of the phantom with higher simplicity. Biomimicry was the next highest weighted category of the design matrix. The scores in this category are based on how well the proposed phantom model can mimic a human brain. This is primarily based on the similarity of the design's MRI scans to in-field MRI scans of intracerebral hemorrhage. The Full-Skull Pressurize model won in this category based on its ability to alter the internal pressure inside of the skull, similar to what a real brain would experience due to hemorrhaging. The durability category is based on how long the phantom model can be effectively used in MRI scans without failure. This category is important for possible mass production. If the model needs high amounts of attention for it to work, it is a bad

product. We scored the Half-Skull and the Full-Skull Non-Pressurized as the winners because the team predicted the pressurizing system would be less durable than having a model without it. And that the Full-Skull Non-Pressurized and Half-Skull models' durability would be equal.
In this category the team gave each proposed model a score based on its replicability. A model's replicability is how easy it would be to replicate the design in a production setting and transport it to a buyer. The team gave the Half-Skull the highest score in this category because transportation would be similar for all models, but replicating the internals of the Half-Skull model would be the easiest. The cost category is scored on the affordability of buying the biomaterials required for fabrication. The team has decided the cost of each individual model should cost between 150 to 200 US dollars. The main costs for the project will be the 3D printed materials associated with the phantom, the different clotting materials, the fluid that will act as the blood inside the head, the polyacrylamide gel, and a pressurized system to mimic the conditions of a human brain. Based on the materials listed the Half-Skull model received the highest score. The safety category is based on the safety of handling the fabricated model, and the safety of the design while performing MRI scans. The Full-Skull Non-Pressurized and Half-Skull model received the same score in this category, whereas the Full-Skull Pressurized received the lowest score because the team predicted the pressurizing system hardware could be unsafe with the magnetic resonance imaging.

Based on the scoring of the design matrix, the Half-Skull and Full-Skull Non-Pressurized received the same high score. After the scoring of the design matrix and the preliminary design presentations, the team decided to move ahead with the Half-Skull model. The team considered going ahead with the Full-Skull Non-Pressurized model but ultimately decided against it. This was because the project is a year long progress and the team predicts they will be able to overcome the challenges involved with the pressurized model along the way. With the Half-Skull model, it's easier to modify the design without major difficulties. In the future, when the team has ironed out the kinks they can replicate the production process with other models in the design matrix to achieve a higher level of biomimicry.

The model chosen based on the design matrix will require PLA to form the 3D print of the skull model and the interior of the brain would be modeled using agarose or gelatine molds as they were found to simulate brain tissue and certain characteristics under right preparation. Approximately, the total cost of this material will be roughly $100-$160, which is below the budget allocated to the team, so monetary wise the team will be well within range. The clot was made using swine blood and a clotting agent (Calcium Chloride) and was placed in a small vial that would ensure the integrity of both the clot and the brain phantom.
The best material for the application of the capsule was PDMS, as it can made into a viscous fluid , soft gel or elastomer. All of these properties would be useful to visualize in the MRI as the artery collapsing in on itself during intracerebral hemorrhaging has a variety of different possible underlying conditions, thus having a material with different material properties would be useful to understand how the capsule would behave in a variety of different conditions. Additionally, it was found that silicon could be visualized in the MRI without causing artifacts that can cause issues to the overall MRI images.

EXPERIMENTAL STUDIES

The final design for the Skull was 3D printed from PLA, matching sinus cavities to make it more realistic. One issue with the Skull model was it was significantly larger for the MRI

machine to be used for testing, hence it was downscaled but with higher infill percentage to avoid seeping through of the gelatine material. To ensure the waterproofness of the PLA skull (since PLA have pores at a micron level) a rubberized sealant spray coating added to remove the pores Gelatin was prepared to mimic the brain tissue, with internal air pockets modeled in gelatine mold. It was fabricated by mixing water and gelatine in powder form, 90 °C for 5 min stirring and left to harden for four hours in the skull chamber and the resulting semi solid modeled brain properties. A Blood clot was modeled as a silicon capsule that was thermoset in a spherical shape with a silicon sealing to make the self healing polymer. Swine blood was used to model hemorrhage with a clotting agent, iron chloride, added to make hemorrhage more visible

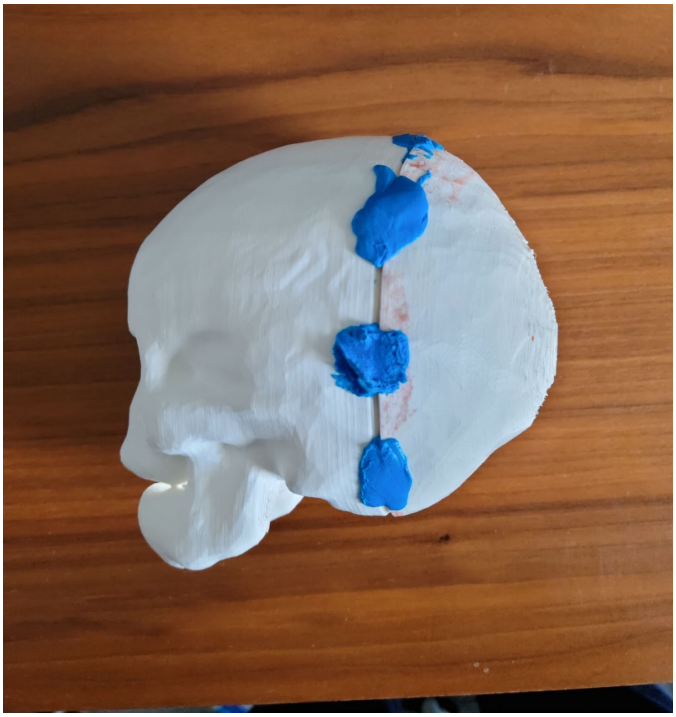

Figure 8. Final Prototype of front half and back-half of the skull connected via water resistant adhesive

Figure 9. Back-half of the skull

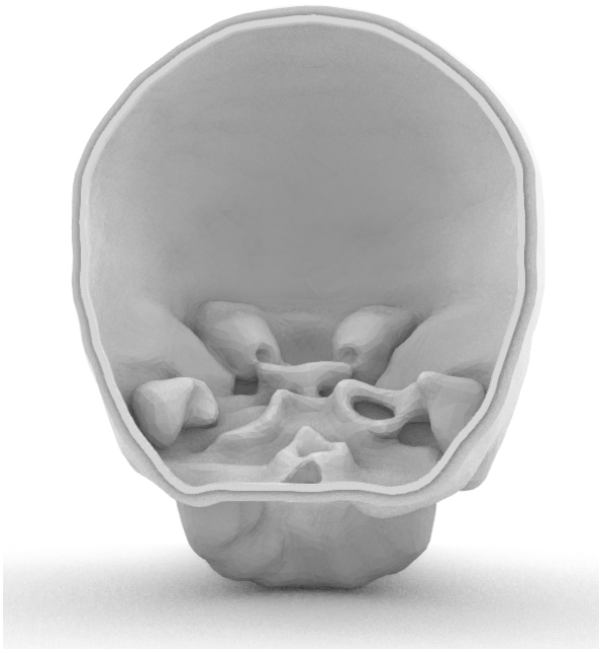

Figure 10. Front half of the skull

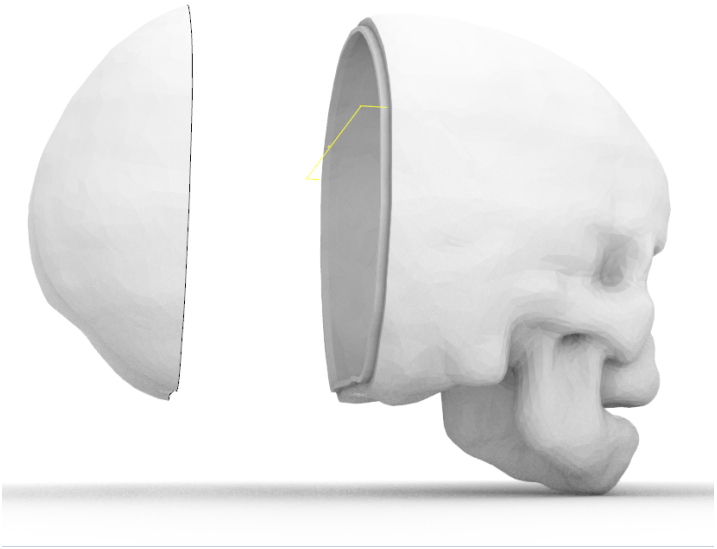

Figure 11. Front and back half of the skull model, side view

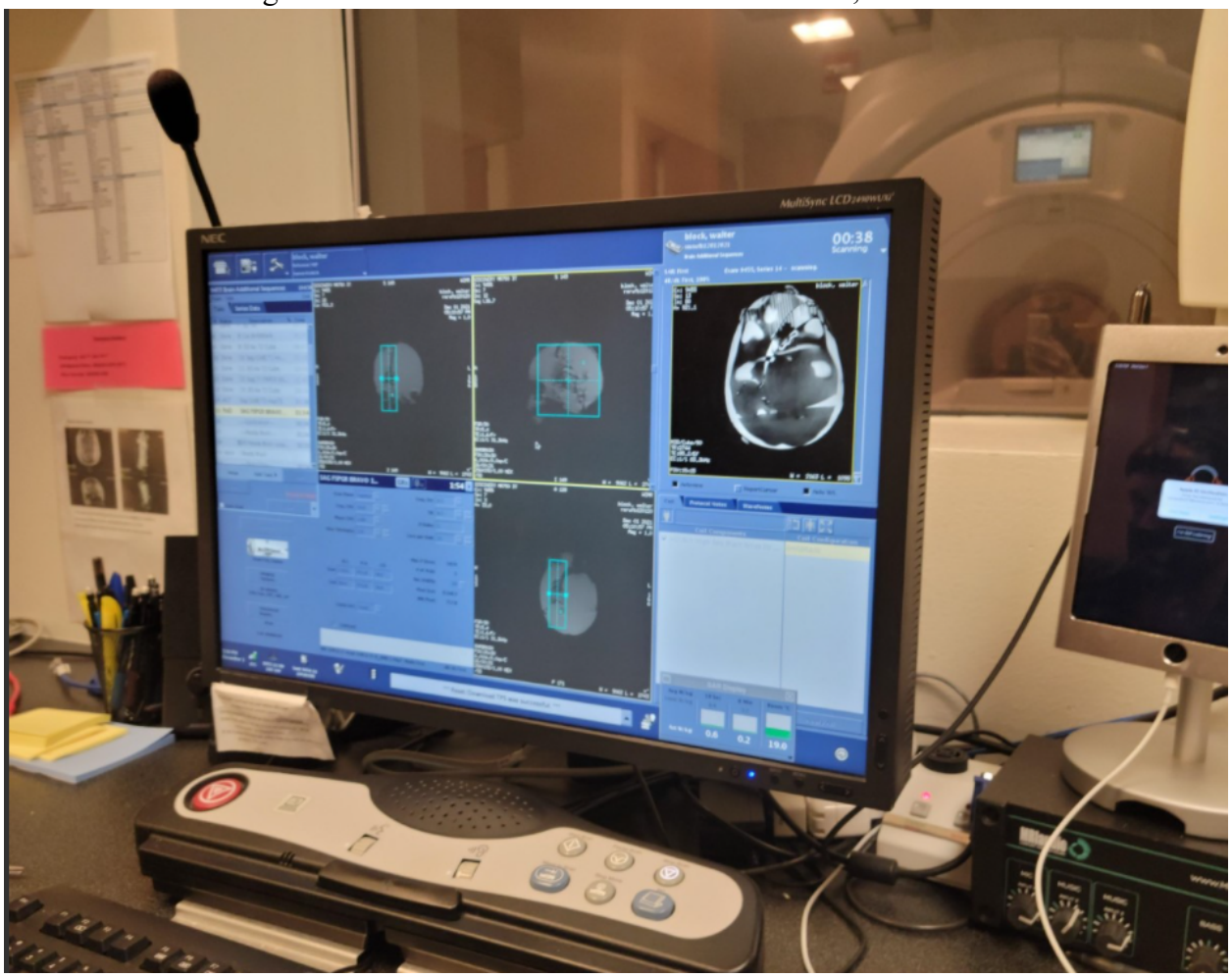

Figure 12. MRI room, scan of the phantom model

After the team's final prototype was complete. The team brought the phantom model to the MRI lab to obtain MRI scans of the model with the clot and without. Multiple MRI scan images sets were obtained to visualize the Signal to Noise Ratios apparent within different sections of the DICOM images The first MRI set focused on just the hemorrhage within the skull without the blood within the capsule The second MRI set focused on the hemorrhage within the skull with the blood within the capsule A third MRI scan of the guided probe was performed to analyse the path of the catheter to the blood clot with RT HOC used to change the real time imaging to see the effects in the case based images

At the MRI lab, the team obtained one T2 scan of the phantom model without the clot present and three T2 scans with the clot present. The MRI scans resulted in the team receiving anywhere from 70 to 180 images for each T2-weighted scan. Once the images were obtained, the team brought the images over to ImageJ for analysis. The first test done compared the presence of the clot in the different scans. Shown below in Figure 13. The team highlighted the area in the MRI images with the capsule and hemorrhage present, then applied the highlighted area to all of the images in the T2 sequence. After highlighting said area, the team analyzed the pixels in ImageJ, an image processing platform that allows analysis of images, and obtained a histogram of the number of pixels for each grayscale value present according to ImageJ as shown in Figure 19. The MRI images of the phantom model without the hemorrhage model were analyzed using the same process by outlining an area equal to the outlined area in Figure 13., and located in the same spot as shown in Figure 14., to give a histogram of the grayscale images as shown in Figure 20.

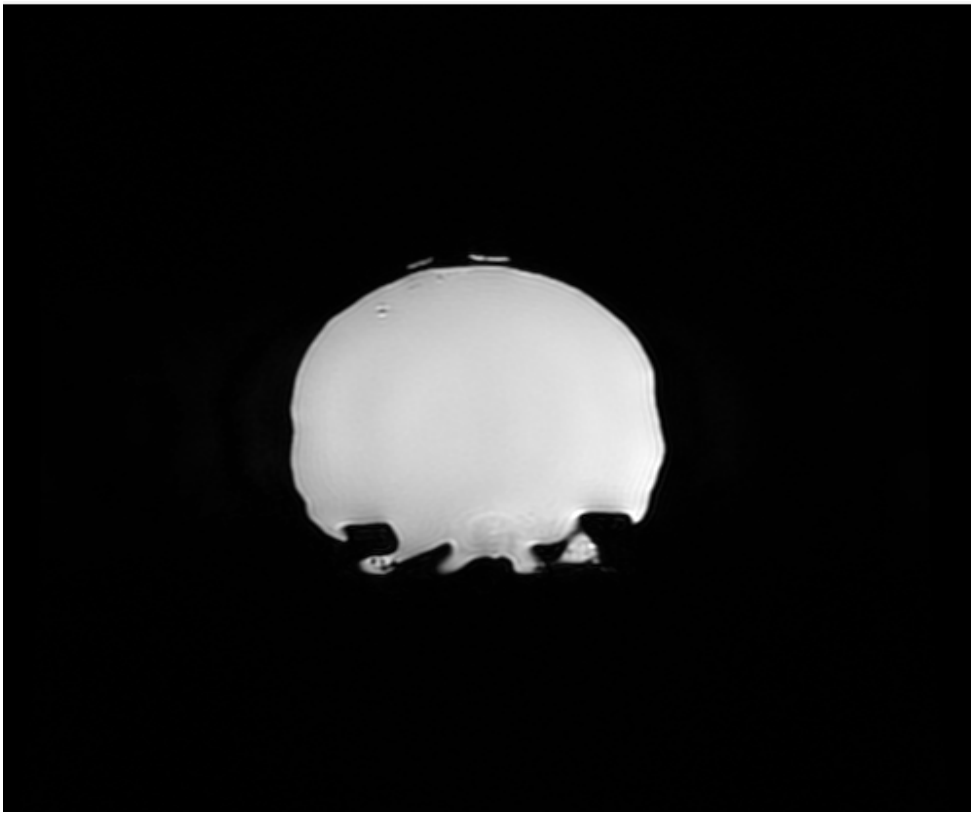

Fig 13 Coronal crossectione clot absent MRI image

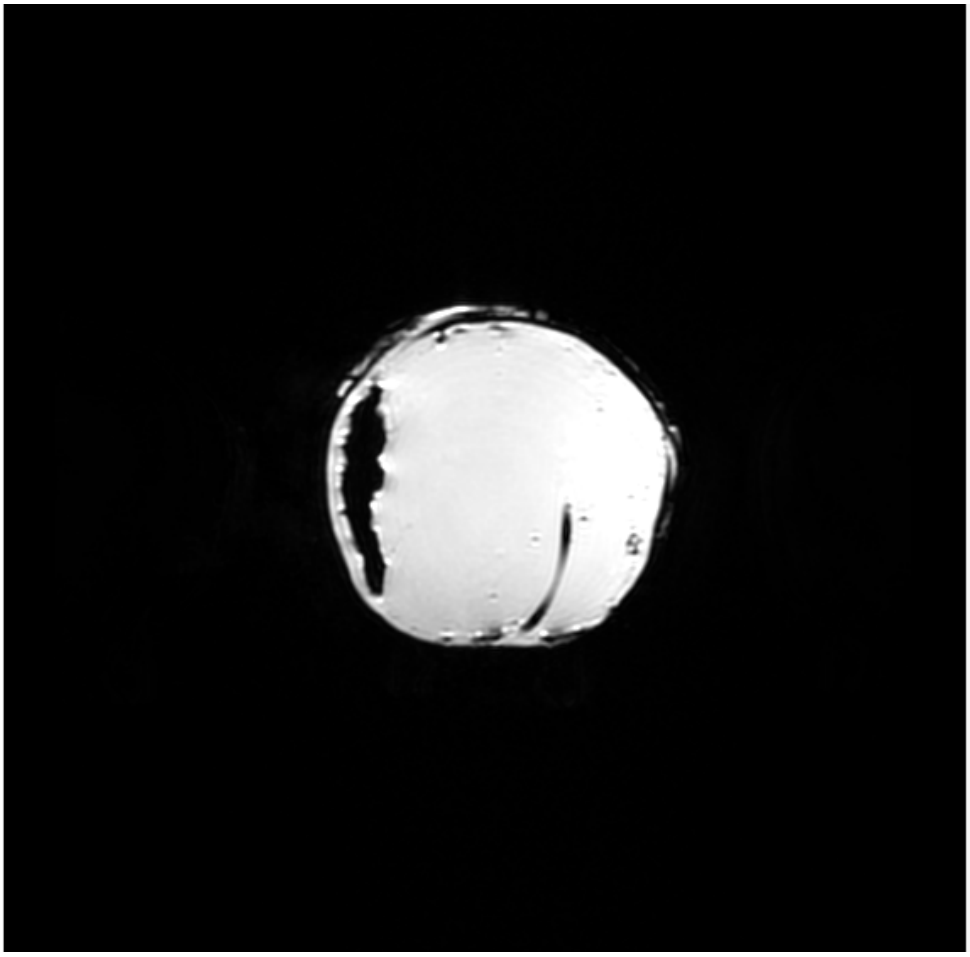

Figure 14. Coronal cross section of the guidance probe present

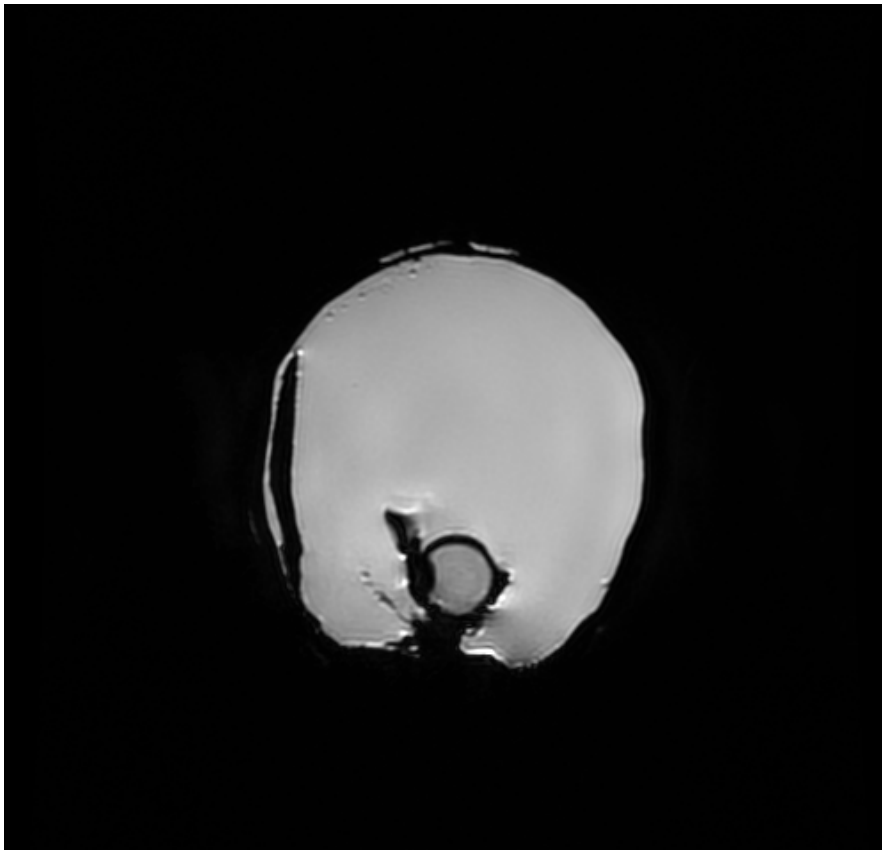

Figure 15. Coronal cross section Blood Clot(high iron) present

In a following test, the non-clot and clot 3pl LOC MRI dicom images were imported into 2 different sampling groups into ImageJ. Once the two sets of images were uploaded, the team wished to look at the total contrast values, which was possible through the histogram feature available in ImageJ that displays the distribution of gray values through the active images. The average of the gray values at the specified positions were obtained and the distinctive difference between the clot and non-clot dicom image was the presence of a larger amplitude in the middle of the histogram as compared to the non-clot image. This signified that towards the center of the phantom, the capsule was able to be visualized and that the values showcased a justafibile difference, which was proven through a statistical test. The reason the team looked at the contrast values of the non-clot and clot phantom models was to see if there was a prevalent difference visible enough for the neurosurgeon to see through an MRI scan to perform the irrigation surgery to remove the hemorrhage.

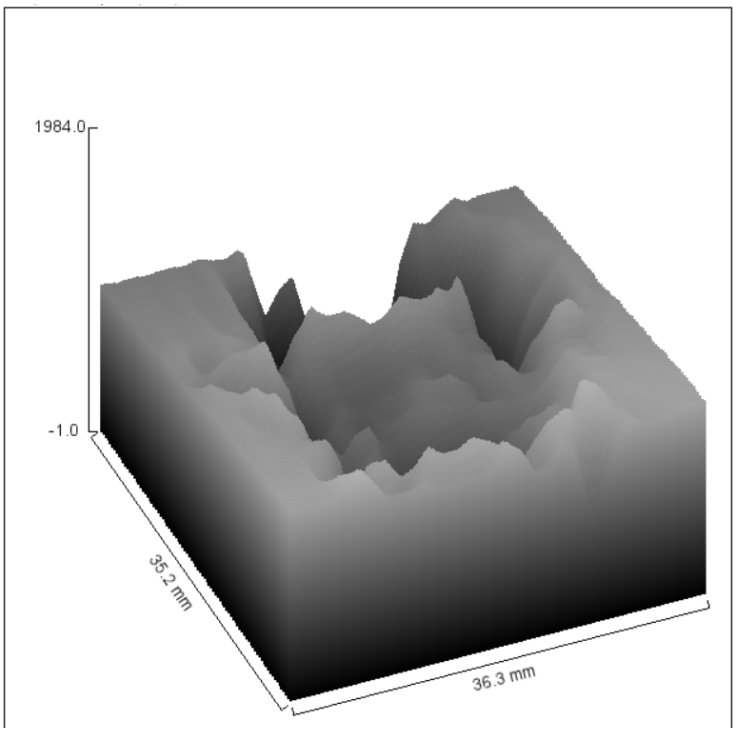

Figure 17. Surface model displaying the clot in the phantom

The following plot was obtained from ImageJ by importing the clot dicom images into the platform and performing the surface plot feature. The reason for this is to locate how the volume of the clot under the MRI image came to be, compared to the actual amount that was put into the capsule into the phantom model. From the above image it was determined that it was approximately 40 cm^3, based on the calculation of 20mm*20mm*10mm. The actual capsule that contained the swine clotting factor was approximately 25 cm^3. There was a difference of 15 cm^3.

Figure 18. shows the grayscale value results associated with the hemorrhage. Excluding outliers, the team determined based on the histogram, the possible grayscale values for the hemorrhage are between 1500 to 2500. The team then took the values from Figure 19. and Figure 20. and excluded all data points below 1500 and above 2500. The team then graphed the number of pixels associated with the grayscale values between 1500 and 2500 for the model containing the hemorrhage and the model without the hemorrhage resulting in Figure 21. and Figure 22. Based on these results, the phantom model containing the hemorrhage had over twice the number of pixels associated for each grayscale value than the phantom model without the hemorrhage. The team then performed a two-sample t-test comparing the phantom model with the hemorrhage and without, assuming equal variances and obtained a P-value of 1.91 x 10^-34.

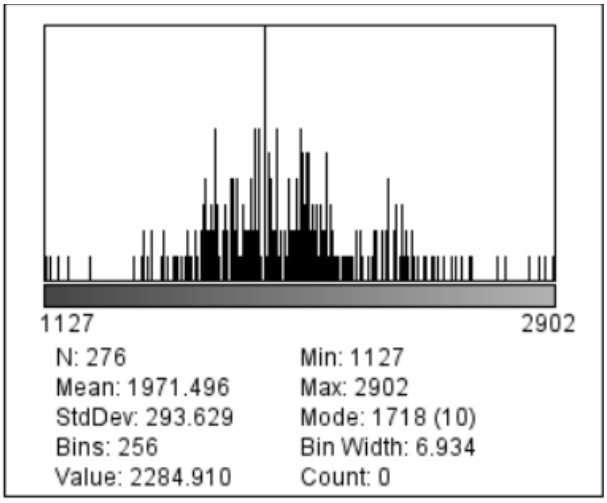

Figure 18. Histogram of the grayscale values with the hemorrhage vessel present, highlighting the hemorrhage

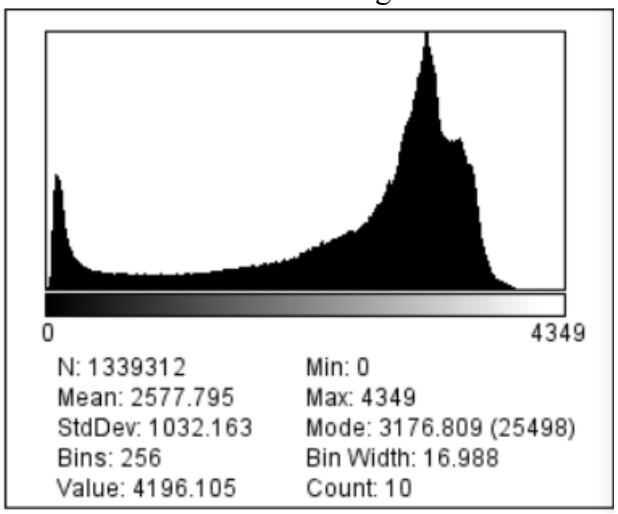

Figure 19. Histogram of the number of pixels per grayscale value, with hemorrhage

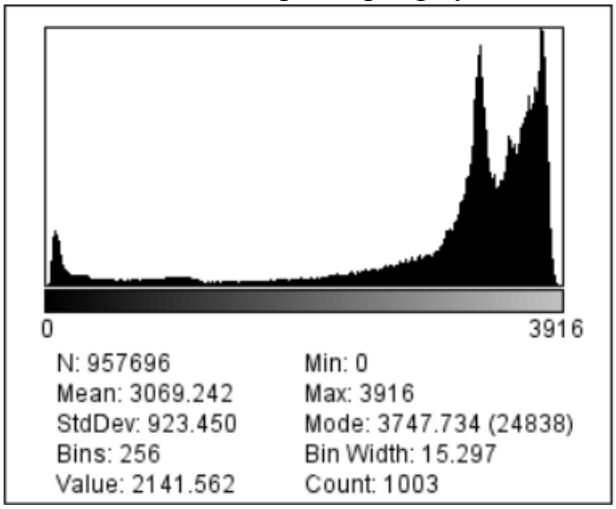

Figure 20. Histogram of the number of pixels per grayscale value, without hemorrhage

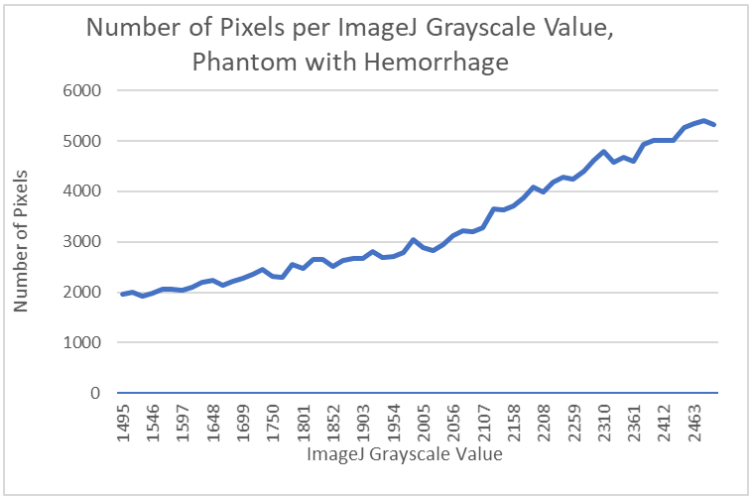

Figure 21: Graph of the number of pixels per grayscale value for the phantom, with hemorrhage

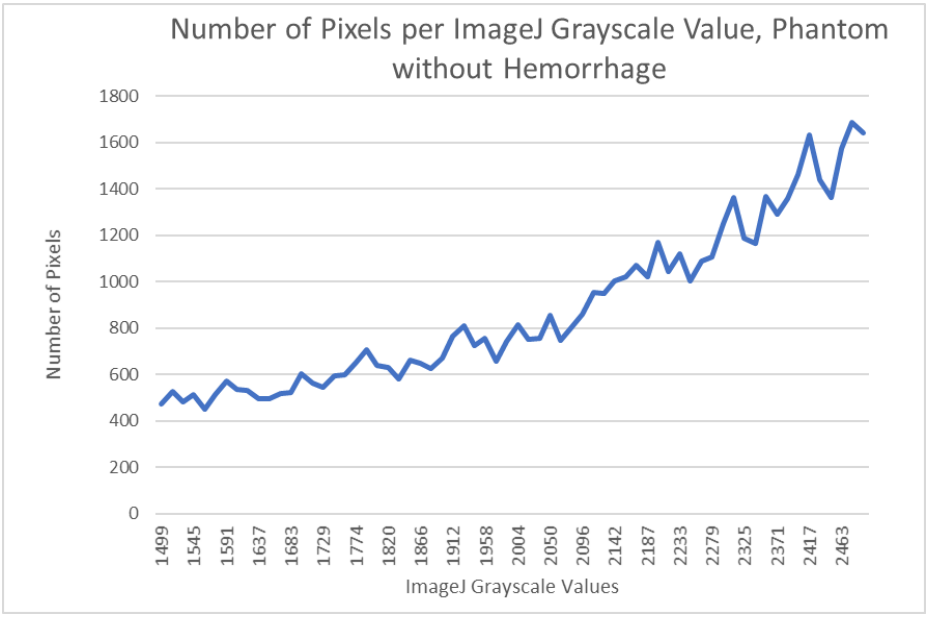

Figure 22: Graph of the number of pixels per grayscale value for phantom, without hemorrhage

Next, when looking at the data for the total contrast between the clot and non-clot histogram, the team looked into making the null hypothesis being that the contrast values of non-clot and clot images showed no difference, while the alternative hypothesis was that there was a difference between the contrast values of the two images. When a 2-sample t-test was performed on the data, where alpha was set to 0.05, the p-value ended up being 0.00178398, which meant the team's null hypothesis was rejected. This indicates that we can reject that there is no difference between the contrast values of the two images. Theoretically, this should transfer over to when the neurosurgeon looks at the images during the MRI scan to determine the best access point to removing the hemorrhage. Additionally, when the data for the surface plot was looked into to determine how the volume of the clot was determined under imaging, it was found that the clot amount was approximately 40 cm^3, while the actual clot was 25 cm^3. When a two sample t-test was performed with this data, where the null hypothesis was that there was no difference between the amount calculated from the image and the actual clot, and the alternative

hypothesis was that there is a difference between the amount determined from the image and the actual clot amount. It was found that the null hypothesis was rejected as the p-value was 0.0002958, which is significantly less than an alpha value of 0.05. This means that the volume that was calculated from the image did not show the actual clot volume accurately and that the team will need to find a better container to put the clot into, or use a clot that has recently clotted and not one that was clotted a few weeks prior to the imaging.

The team focused on testing the efficacy of the images that were obtained via the MRI, by measure of SNR from several DICOM data image sets, in the order they were obtained. The images were obtained in an order where the first MRI set focused on just the hemorrhage within the skull without the blood within the capsule. The second MRI set focused on the hemorrhage within the skull with the blood within the capsule. Finally, the third MRI scan was of the guided probe that was performed to analyze the path of the catheter to the blood clot. While the MRI scans were taking place, the team used RT HOC to change the real time imaging to see the effects in the case based images. The team were able to obtain images that matched certain expectations from the client, however further analysis and statistical testing was needed to be completed to actually test how valid the images were based on Signal to Noise Ratio. This is a measure that compares a certain level of an actuated signal to the background noise present in the image. This is an important measure as higher quality images should have SNR values greater than 10 and less than 75, signifying that their value of the images could be used for future analysis. The procedure was done in MATLAB by taking the highest quality image slice for a particular image set and then adjusting the dynamic range of the image to center the range to roughly where the hemorrhage was present within the skull. The results were then found that the image set of the clot within the skull without the hemorrhage added in displayed a value of roughly 18.5, then the clot within the skull of the hemorrhage was found to be 10.1, and the clot within the skull with the catheter puncturing the clot within the skull was found to be 5.3. Afterwards, a statistical 3-sample t-test was performed to see if there was significant difference between the three different SNR, and a value of 0.032456 was obtained, indicating a statistical difference between the data sets.

Figure 23. Coronal crossectional clot absent MRI image

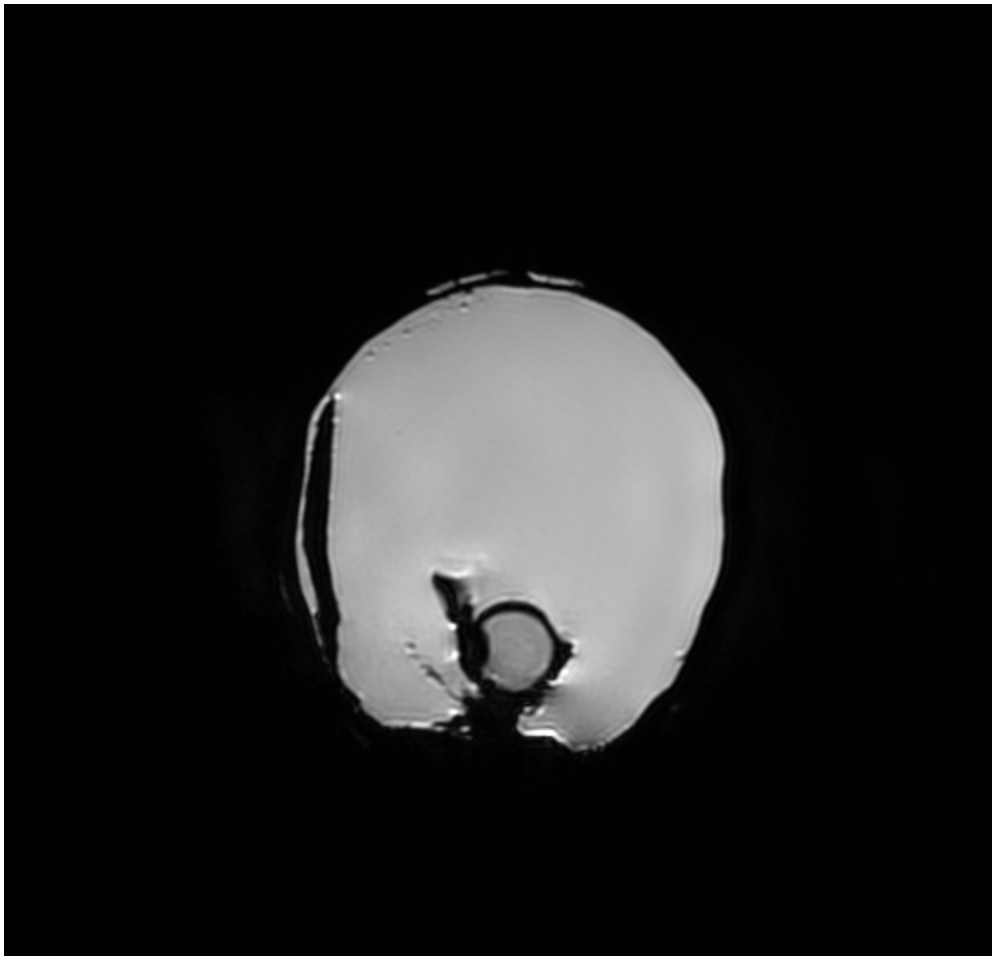

Figure 24. Coronal cross section Blood Clot(high iron) present

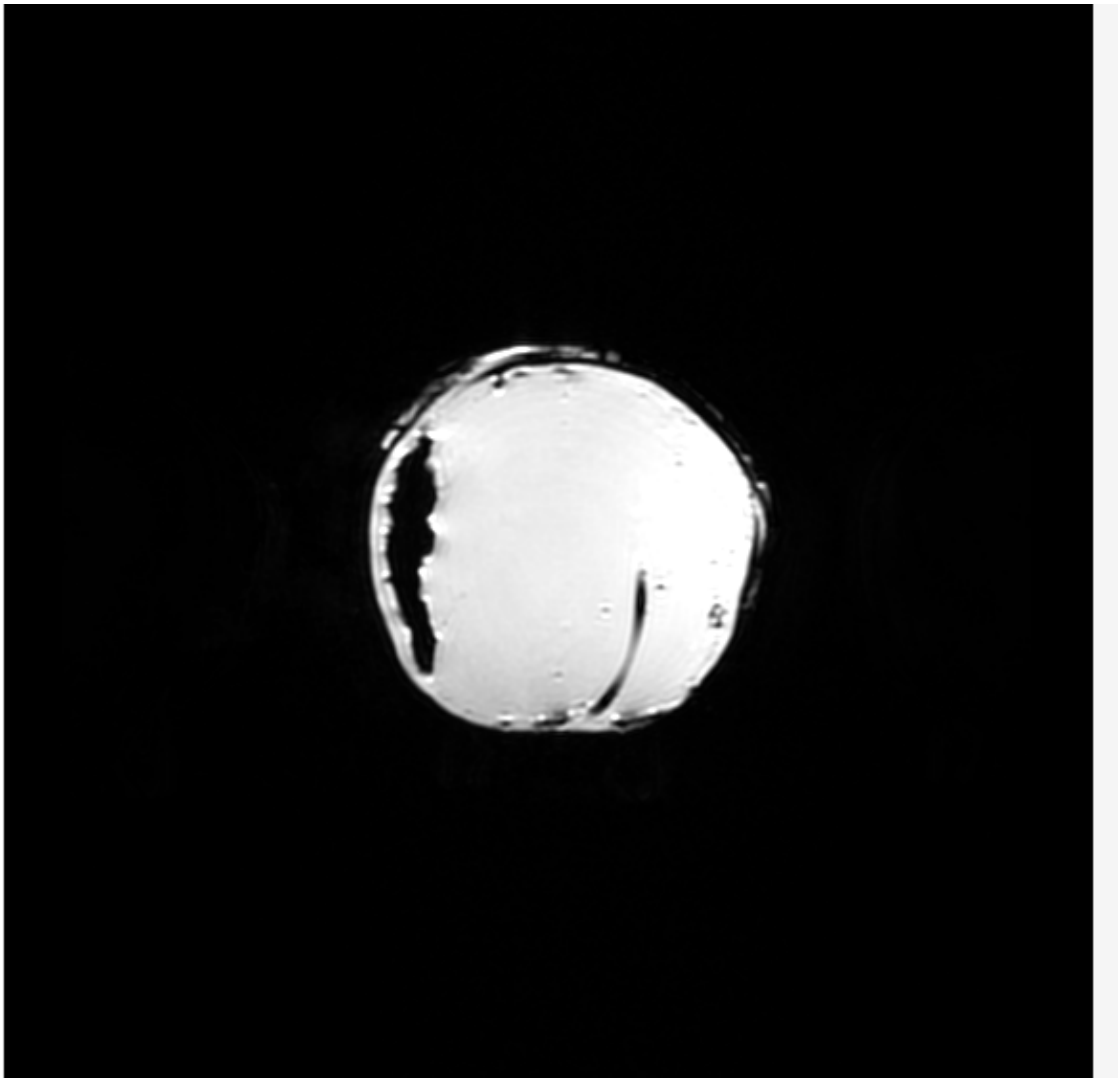

Figure. 25 Coronal cross section of the guidance probe present

DISCUSSION

When completing the final design for the skull model, there was a cross sectional area that was blacked out because of a one inch separation between the top and bottom half the skulls when the gello was encased into the phantom. These caused strike deviations in the contrast values by adding larger than expected values for the images with the dark strikes in ImageJ and in the histogram. Additionally, when the team put the capsule that contained the blood vial into the phantom skull model, parts of the gel had to be removed to allow it to be placed in. This led to deviations in the clot imaging displaying holes where, in reality, the capsule was simply pushed into the gelo. These errors will be fixed in the final phantom model by combining the two halves of the skulls together before pouring the gel into them and having the capsule put into the phantom before the gel gets poured in. Another error was that the team was provided with a blood sample that was two weeks old, which could lead to less clots being formed [12] leading to

less clots seen on the MRI scan. One change that will be made in the final phantom model will be the inclusion of access holes that will allow the actual removal of the hemorrhage with a catheter and adding clotting factors to different locations in the phantom to allow for the visualization of removal of clots in a more accurate setting. In addition, the team will need to figure out a better capsule to hold the clotting swine blood as it was apparent that the capsule size from the images did not match the actual size.

Gelatine was prepared under specific conditions to model the brain tissue and swine blood mixed with a clotting agent, so it could be used to create the clot under the MRI scanner. The images obtained from the MRI testing were quite promising as the team obtained clear images of the clot. One major obstacle the team ran into was the cracking of the gelatine phantom while placing the clot. The crack was visibly seen in the images. Another pitfall was the placement of the clot and air pockets, initially the team decided to create separations in the phantom membrane using PLA supports. However, the PLA support was not fabricated as expected which led to seepage through the support decreasing their separation.

The team's results illustrated that there was a significant difference between the contrast of the clot and non-clot dicom images and that the value calculated of the capsule volume was significantly different then the experimental one.

The goals for this semester include printing a larger, life size skull model that will also contain a pressurized system that will match the conditions in the blood and require more puncture force. The team might need to change the conditions used to make the gelatine model, in order to avoid cracking. Afterwards, the team will create replica hemorrhages with swine blood combined with clotting agents. The swine blood will then be injected with a needle into the phantom model at a desired location. The team will also create air pockets in the phantom by injecting air into the gelatin model with a needle at desired locations, if this method is not successful, the team will 3D print PLA pieces to mimic air pockets since they should not show up on the magnetic resonance imaging. Also, the team will make more models that will have different locations where the swine blood capsule will lay, so the catheter can enter at different angles and have a more accurate setting. It will also be important for the team to perform actual statistical testing with physician analysis to determine the efficacy of the positioning of the hemorrhage pockets. Lastly, the team could potentially include an electronic transmitter that shows the correct color when surgery is done successfully, or the wrong color and location if the incorrect part of the brain is removed or punctured.

Another important goal is to develop a blood carrying capsule that will be able to withstand the pressure from the encompassing jello that acts like the brain. The capsule should be able to get punctured by a catheter, so the coagulated pig blood inside can be accurately and efficiently removed. In addition to the capsule development, there will also need to be holes for access points to be added into the skull, so the catheter can be placed inside and the neurosurgeon will be able to visually see it penetrating the capsule from the top of the skull. This will come closer to meet our client’s needs as the client is looking into the development of a model that will contain an artery like capsule where the hemorrhage would originate from and a surgical device will be tested for removing the clot from that specific location. We plan on finishing the following part of the project this week and meet with the client and the neurosurgeon in the following week to go over the design and give him the files of the completed design and see what developments need to be made. In accordance with those changes, the team will move to make changes with the final design, so it will be ready for actual clinical testing with the client and his team. The following steps on the project depend on the time available

after the following developments. These steps include designing a pressurized system, using a vacuum, where the contents inside the skull will match the conditions of an actual brain. Additionally, the development of a hemorrhage at different locations is another aspect of the design the team will also incur.

The neurosurgeon will practice removing the clot. Then, based on how many times the neurosurgeon is successful on removing the clot a set number of times, the team will determine accuracy and efficiency of the model. The team will make changes based on how well or poorly the physician performs and makes it to the intended target. Next semester, the team plans to test the absolute final design by having adjustments based on that. From those adjustments the team will test the neurosurgeon again and see the differences in his performance.

The team's focus of this semester was to look at the most biocompatible clot that would mimic the conditions of an actual hemorrhage within the brain and one that can be self-healing and be able to condition itself back to its original nature after multiple puncture sites from catheters and syringes to place coagulated blood within the system. From extensive research, Silicon was found to be attributed as the best compound to match these expectations as,

Most normal transudation of microscopic amounts of silicone gel cannot be detected by MRI scans. It would be best to use PDMS as polyurea-urethanes based on hexane diisocyanate modified polyether-PDMS soft segments show three distinct phases: a PDMS-rich phase, a polyether soft-segment-rich phase and a hard-segment-rich phase. When evaluated for their blood-contacting properties in a canine *ex vivo* model, they had lower adherent platelet and fibrinogen deposition when compared to a polymer without PDMS in the soft segment [15].

Additionally during this semester, the team looked at how the silicone clot would perform under the MRI, when coagulated blood would be present and when the catheter would puncture the silicone capsule to encompass a drainage technique, where the blood would be able to drain out of the chamber. For this reason, the team looked at scanning the clot, the one that best determined to best mimic the conditions of an actual human artery, and see how it would behave under various conditions. From the scans and statistical analysis, it was found that the clot was able to be visualized under the MRI and could potentially be used as a neurological model.

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