BMEN 509 Project Report: DICOM File to 3D Print Pipeline

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*Many pages contain full images depicting the pipeline process and results.

1. Introduction

This project aims to develop a pipeline for converting DICOM (Digital Imaging and Communications in Medicine) files into physical 3D models of anatomical structures. DICOM files, commonly used in medical imaging, contain detailed information about the internal structures of the human body captured through techniques such as CT scans and MRI.

Our primary objective is to establish a comprehensive workflow that efficiently processes DICOM data, isolates specific anatomical structures, generates clean and accurate mesh data, and ultimately prepares models for 3D printing. This will involve utilizing various techniques, including segmentation and thresholding, while also considering factors such as printing supports and image noise.

The human body is a fascinating structure of tissues and bones that cannot be studied comprehensively through mere observation. Creating accurate representations becomes indispensable, given the inherent challenge of visualizing internal anatomy. While two-dimensional visuals offer some insight, three-dimensional models can breathe life into visualizing internal anatomy.

Using three-dimensional modelling to explore internal structures holds vast potential across various domains. These applications range from in-depth analysis of anatomical features to the design and fabrication of prosthetic devices. Moreover, such models serve as tools in patient education, aiding individuals in comprehending their medical conditions and diagnostic results. Additionally, they play a pivotal role in medical education, helping students understand their education better.

Throughout this project, we will explore various methods and tools, analyze the effectiveness of different techniques, and document our findings to establish best practices for DICOM to 3D print conversion.

2. Background

In this section, we provide an overview of the software tools utilized in our project and delve into the theoretical concepts underlying the methods employed.

3D Slicer is an open-source software platform designed for medical image informatics, processing, and three-dimensional visualization. It offers support for various file formats and is compatible with imaging modalities such as MRI, CT, and ultrasound, making it essential for processing and manipulating DICOM data, which is crucial for our project's objectives. We primarily utilize 3D Slicer for segmentation and thresholding tasks.

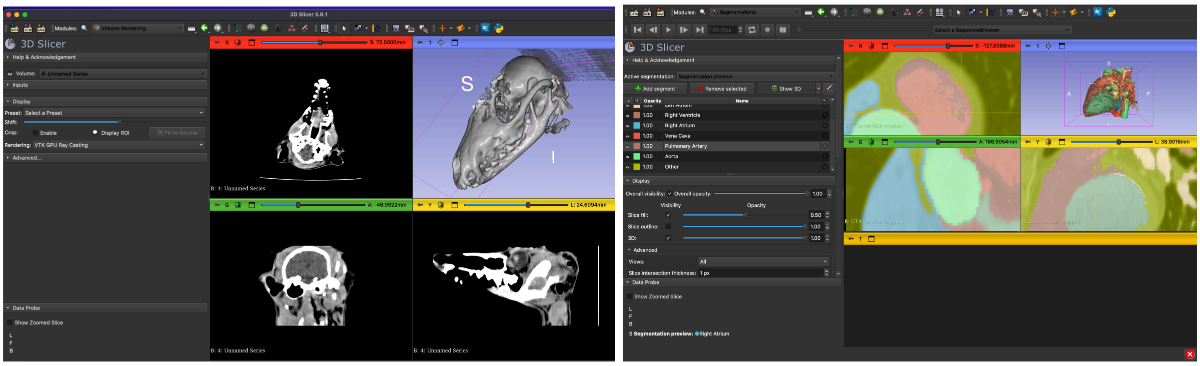

Figure 2.1. The Volume Rendering page of 3D Slicer(left), shown here is the thresholding to get a render of a fox skull through thresholding. The Segment editor(right), is shown here creating a 3D model of a heart using segmentation.

Segmentation(fig 2.1) involves partitioning or separating an image into multiple regions or segments. While 3D Slicer provides tools to automate segmentation, it often requires manual intervention. By isolating desired structures, segmentation facilitates accurate analysis, visualization, and measurement of anatomical features, supporting tasks such as organ volumetry and treatment planning.

Thresholding(fig 2.1) is a straightforward process used to distinguish objects or regions of interest based on their pixel intensity values. It offers a relatively simple way to separate anatomical structures from background or surrounding tissues, aiding in the creation of accurate 3D models.

STL (Stereolithography) is a file format widely used in 3D printing and computer-aided design (CAD). It represents a 3D model's surface geometry as a collection of interconnected triangles. STL files are commonly used for their compatibility with various 3D printing software and hardware. They can be edited using 3D modelling tools such as Blender.

Blender(fig 2.2) is a widely-used open-source 3D modelling software known for its comprehensive suite of tools applicable to various modelling tasks. While commonly associated with animation and video game development, Blender's functionalities extend to 3D printing preparation. Add-ons such as the 3D Print Toolbox streamline the process of preparing models for 3D printing.

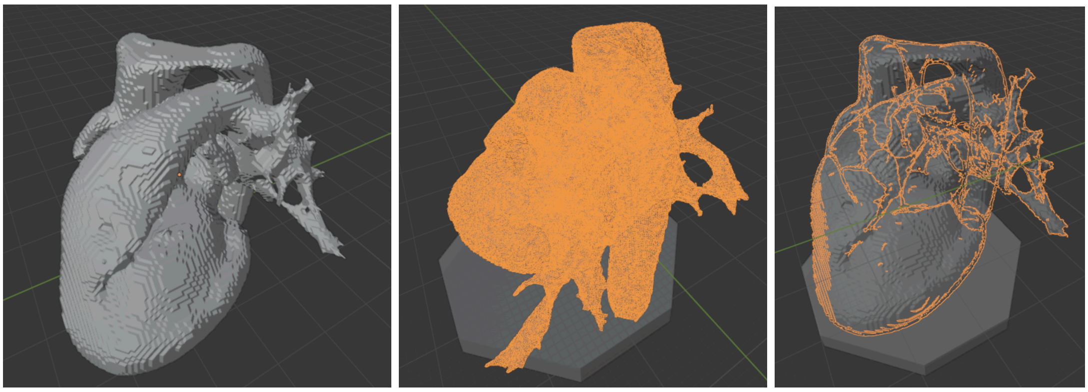

Figure 2.2. Working on the heart print in Blender. Displays the Mesh(left), selection of all data points(middle) and the transparent mesh. A platform has also been added to this model as a second object within Blender.

3. Methods and Materials

This section outlines the methodology and materials utilized in our project to establish a pipeline for processing DICOM files into physical 3D models. We present a step-by-step procedure and discuss secondary objectives, including recording results and observations throughout the pipeline's development.

3.1 Project Goals

Our project encompasses four primary objectives:

1) **Creation of a DICOM to 3D Print Pipeline:** Develop a streamlined workflow to convert DICOM files into physical 3D prints.
2) **Comparison of Bone and Tissue Printing:** Investigate differences between printing bone and tissue structures, exploring challenges and considerations unique to each.
3) **Evaluation of Mesh Creation Methods:** Test various methods for generating 3D mesh objects, including automatic thresholding and manual segmentation, to determine their effectiveness and accuracy.
4) **Assessment of Articulating Prints:** Assess the feasibility and ease of creating 3D prints with articulating joints and hinges, exploring their potential applications and challenges.

These goals guide our methodology and experimental approach, driving our efforts to establish a robust pipeline for DICOM to 3D print conversion and evaluate its efficacy across different scenarios and applications.

3.2 Datasets

Various DICOM files sourced from different repositories will be used in our analysis(fig 3.2.1):

Fox Skull from InVesalius [7]:
This DICOM file serves multiple purposes, including evaluating mesh creation with varying supports and testing the concept of creating an articulating print by separating the jaw from the rest of the skull.

Human Skull from Medimodel [6]:
The human skull DICOM file from Medimodel is employed for the noise test. We create a default print from the file and then repeat the operation after introducing salt and pepper noise and Gaussian noise.

Human Jaw from Medimodel [6]:
This dataset is utilized to test creating an articulating print by cleaning up the jaw and separating it from the upper teeth.

Human Heart Using 3D Slicer Sample Data [5]:
The DICOM data sourced from 3D Slicer sample data repository is utilized for organ/tissue print and segmentation. Our goal is not only to separate the whole heart but also to isolate individual sections such as the right atrium.

Human Spine from DICOM Library [8]:
The DICOM file obtained from the DICOM Library is employed to test mesh cleanup and the use of different printing supports.

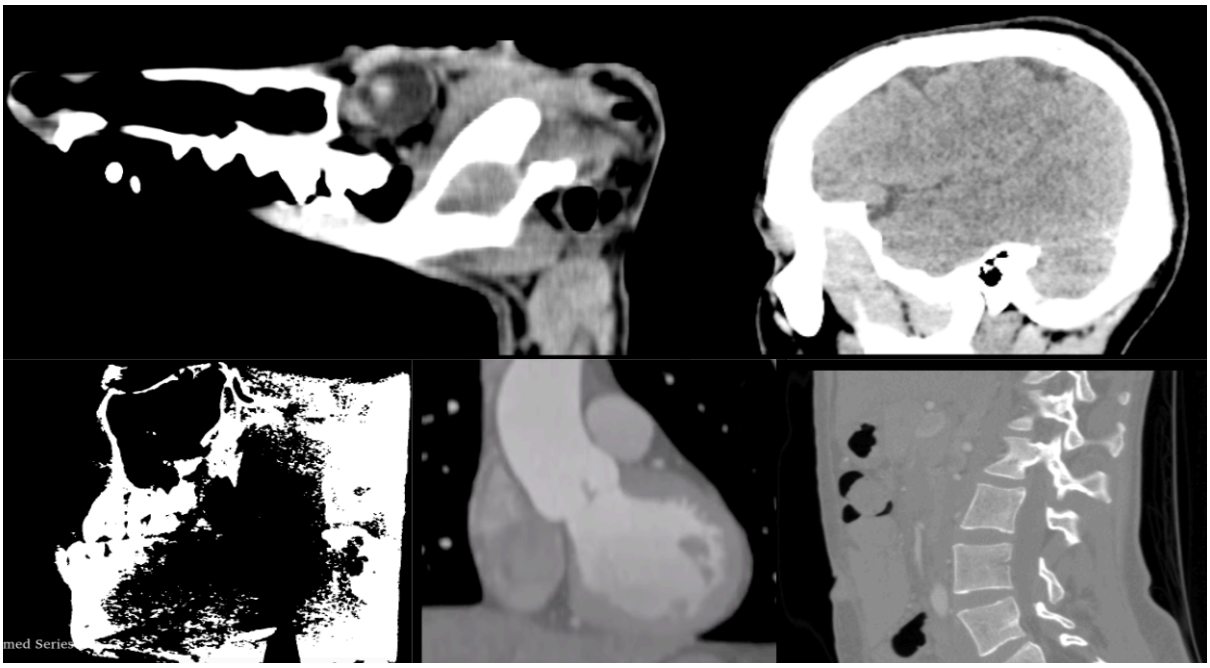

Figure 3.2.1 The original unaltered files are seen at a side view. Fox Skull(top left). Human skull(top right). Human jaw(bottom left). Human Heart(bottom middle). Human Spine(bottom right).

3.3 Tools

1. **3D Slicer:** Software for segmentation and thresholding. Exports an STL file/
2. **Blender:** Mesh cleaning and adding manual supports(fig 3.3.1). Clean the STL file.
3. **3D PrinterOS:** For adding printer supports if no manual supports are added. Last check to ensure the file can be printed correctly. Converts the STL file to a gcode file which can be used by a 3D printer.
4. **3D Printers:** Located at the U of C MakerSpace. Create a physical print

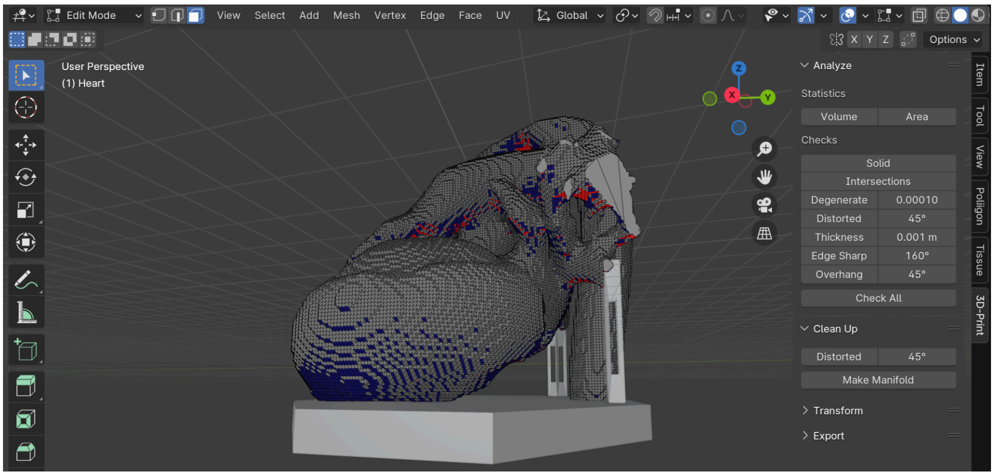

Figure 3.3.1. Blender processing of the heart. Displayed are some of the 3D Print Toolbox[11] options to check for problems with printing and correct issues that would prevent a clean print. This checks for overhangs and mesh edges that cannot be printed.

3.4 Pre-Process Data

Before creating 3D models from the DICOM files, we wanted to explore how different data qualities affect the process. Most of the datasets were already well-prepared with appropriate image processing. We decided to add some controlled variations to one dataset to make our study more diverse. This was done to see how these variations would impact the accuracy of the 3D models we create.

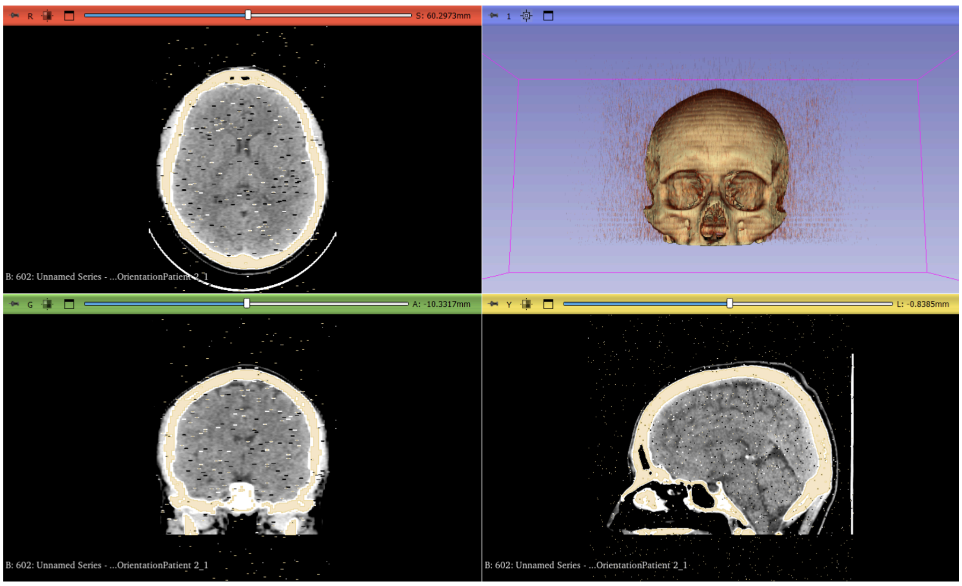

Figure 3.4.1. 3D Slicer shows the human skull file after the Salt and Pepper noise has been added.

To do this, we intentionally added two types of noise to the DICOM files representing the human skull: salt and pepper noise(fig 3.4.1), which creates random black and white dots, and Gaussian noise, which adds smoother, subtle changes in intensity. These types of noise mimic what can happen in real medical imaging scenarios.

3.5 Extract Mesh Using 3D Slicer

In our workflow, we first uploaded the DICOM files into the 3D Slicer software. Then, we performed segmentation, a process where we delineated specific structures of interest within the images. Additionally, we utilized thresholding, an automated detection feature in 3D Slicer, for the rest of the files. Thresholding involves distinguishing objects based on their intensity values in the images. Next, we exported the resulting mesh data for further processing and printing.

3.6 Clean the Mesh Data Using Blender

In the next step, we focused on cleaning the mesh data in the resulting STL file. This task was carried out using a 3D modelling tool called Blender [2]. Cleaning involved a series of operations aimed at refining the mesh and ensuring its readiness for 3D printing. These operations included removing duplicate vertices to eliminate overlapping positional data, fixing normal faces to ensure the correct orientation of face directional vectors, and removing non-manifold edges to address shared edges between faces. Additionally, we filled holes in the mesh, smoothed out surfaces that were noisy or rough, and decimated the mesh to reduce unnecessary data bringing the file to a manageable size. Furthermore, we added simple manual supports(fig 3.6.1) to enhance the printability of complex prints. The files for the human jaw and fox skull had the jaw separated as an individual model for articulate joints. This comprehensive cleaning process was essential for optimizing the mesh data for successful 3D printing and ensuring the accuracy and integrity of the final printed models.

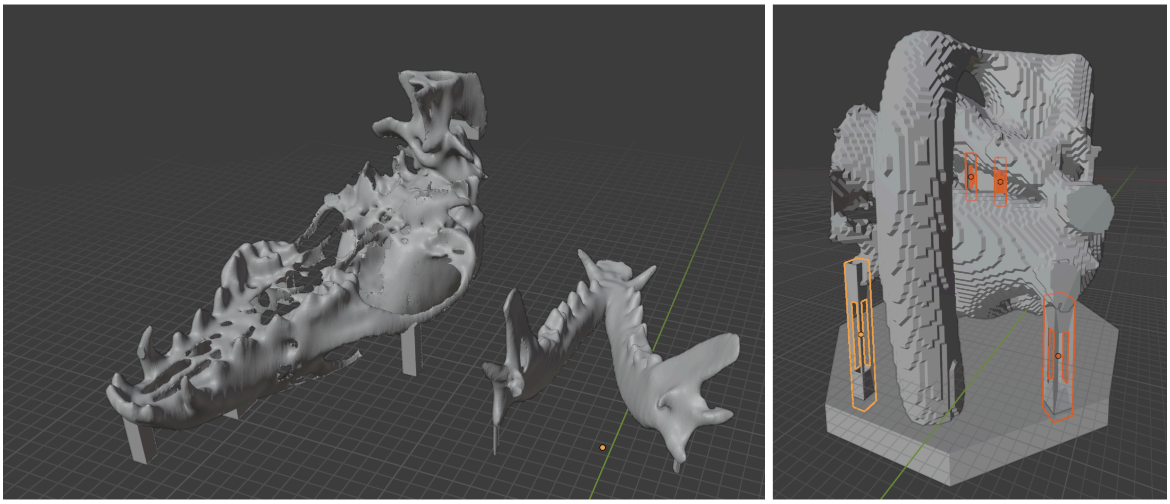

Figure 3.6.1. Seen here are some manual supports added to the fox skull and the human heart. The 3D printing software we used had an option to add supports but it would add support to any section with an overhang. This option enabled fast printing time and support in areas that wouldn't affect or hinder the ability to see the final print.

3.7 Printing the Model

Following the mesh cleaning process, our attention turned towards preparing the model for printing. This involved slicing the mesh into printable layers using 3D PrinterOS [1]. Through this software, we fine-tuned parameters such as layer dimensions and infill density, ensuring optimal print quality and structural integrity. Additionally, we generated a G-code file, which serves as instructions for the 3D printer, guiding its movements and layering process. One possibility for printing was to add printer supports(fig. 3.6.1) These supports are visible on any part of the mesh that is overhanging and were an alternative to manual supports with Blender.

Once the model was sliced and the G-code generated, we proceeded to print the model using the printers available in the Makerspace [3]. Upon completion of the printing process, we undertook final cleanup tasks to refine the printed model such as removing supports and cleaning up small printing errors.

4. Results

In total, 11 prints were created:

- **Human Spine Prints:** Three prints of the spine were created using thresholding. One print had printer supports, another had no supports, and the third had manual supports.
- **Fox Skull Prints:** Three prints of the fox skull were created, all using thresholding. One print had printer supports(fig 4.1), another had the jaw and skull separated, and a larger version of the individual jaw.
- **Human Skull Prints:** Three prints of the human skull were created using thresholding, each with different types of noise: no noise, Gaussian noise, and salt and pepper noise.
- **Human Jaw Print:** The human jaw was printed once using thresholding, with separate upper and lower teeth.
- **Human Heart Print:** The heart was printed once with segmentation, showing the results of tissue and segmentation.

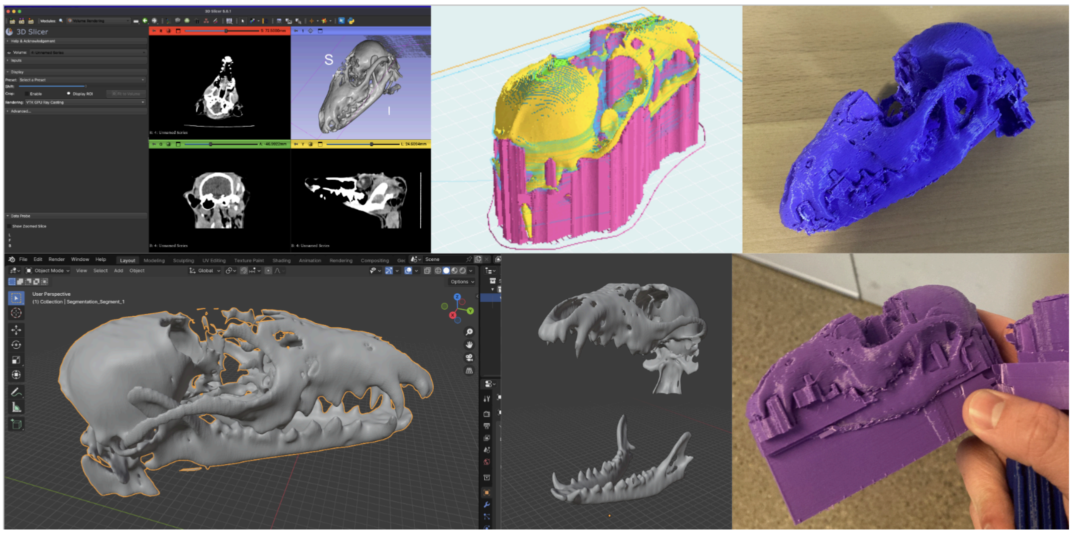

Figure 4.1. The complete process of the fox skull using supports. The supports covered a large area of the print and made it difficult to see the structure. Normally these supports are easy to remove but if they are embedded within the model's hollow areas they become difficult to remove. They were able to be removed(top right) but the hollow areas couldn't remove the entirety of the supports.

The pipeline(fig 4.1) was established and the final results of it are in the form of physical 3D prints and observations regarding the process. While most of the observations were physical, there are a few process observations worth noting:

The human heart(fig 4.2), which was made using segmentation, resulted in much less data passed to Blender and a much faster print time. It was also very easy to clean up in Blender although it took longer to create within 3D Slicer. While it had some sharp corners it was one of the best prints.

Segmentation in 3D Slicer took significantly longer to create compared to thresholding, up to 30 minutes. Thresholding, on the other hand, took around 2 minutes to complete but required more time to clean up the STL file afterwards.

Prints that used manual supports were the cleanest and showed the structure best. Printer supports tended to obstruct the structure more and were difficult to remove (see Fig. 4.4 and Fig. 4.5).

Using Thresholding on the Human Heart was difficult as it was surrounded by other tissue and didn’t stand out as much as bone but the segmentation showed that creating a print of organ tissue was just as efficient as bone using segmentation.

The effect of noise(fig 4.6) showed that the Gaussian noise smoothed out the skull and led to a slightly better print than the default. Salt and Pepper made the print look more like a golf ball and lowered the quality of the print. The speed for creating the prints remained the same in all 3 tests.

The human jaw(fig 4.7) and the fox jaw(fig 4.5 right) showed the potential for articulate prints and the ability to adjust a jaw in this instance.

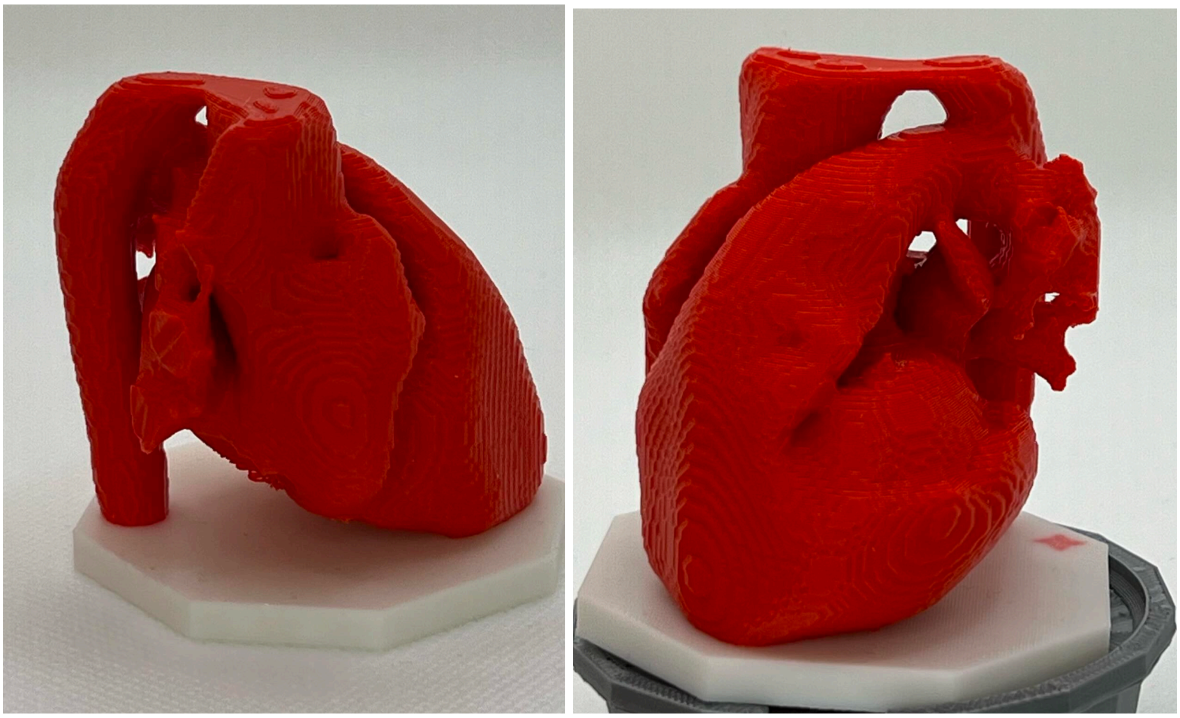

Figure 4.2 The final result of the heart from printing. This used manual supports.

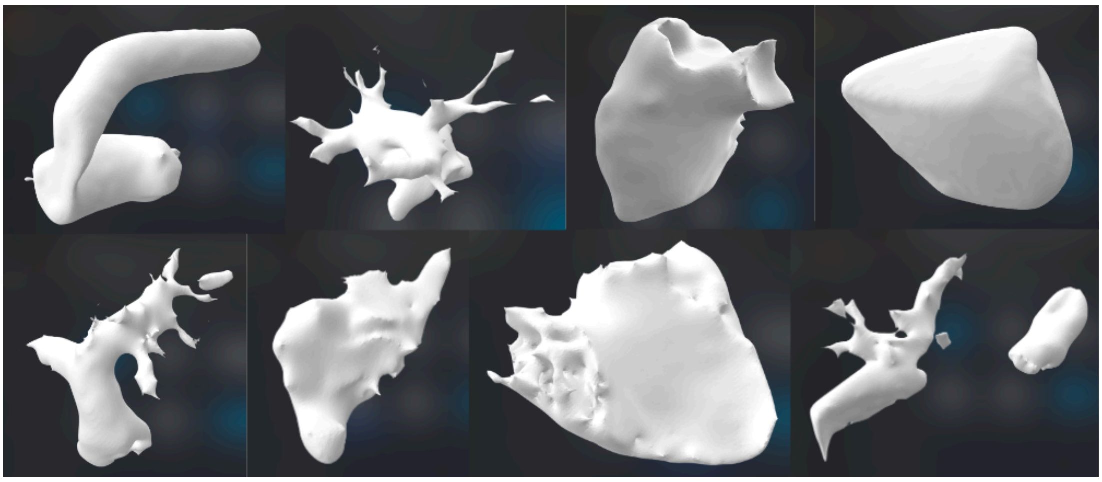

Figure 4.3 Individually segmented sections of the heart. While these weren't printed, they showed that segmentation is a powerful tool for isolating tissues. From left to right and top to bottom the sections are: Aorta, Left Atrium, Left Ventricle, Pericardium, Pulmonary Artery, Right Atrium, Right Ventricle and Vena Cava.

Figure 4.4. The same spine model is printed with printer supports, no supports and supports made in Blender. The last one has the cleanest look and the least printing errors.

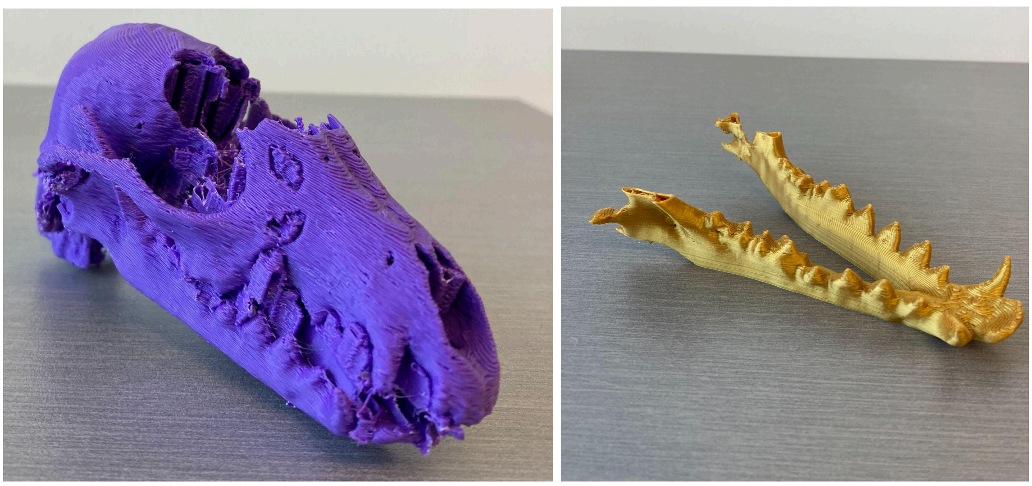

Figure 4.5 The fox skull was not a great print due to lack of initial data but the jaw was able to be separated quite well and output as an individual print.

Figure 4.6. The same skull was printed with thresholding three times. Each skull has a different level of noise. No noise(left), salt and pepper noise(middle) and Gaussian noise(right).

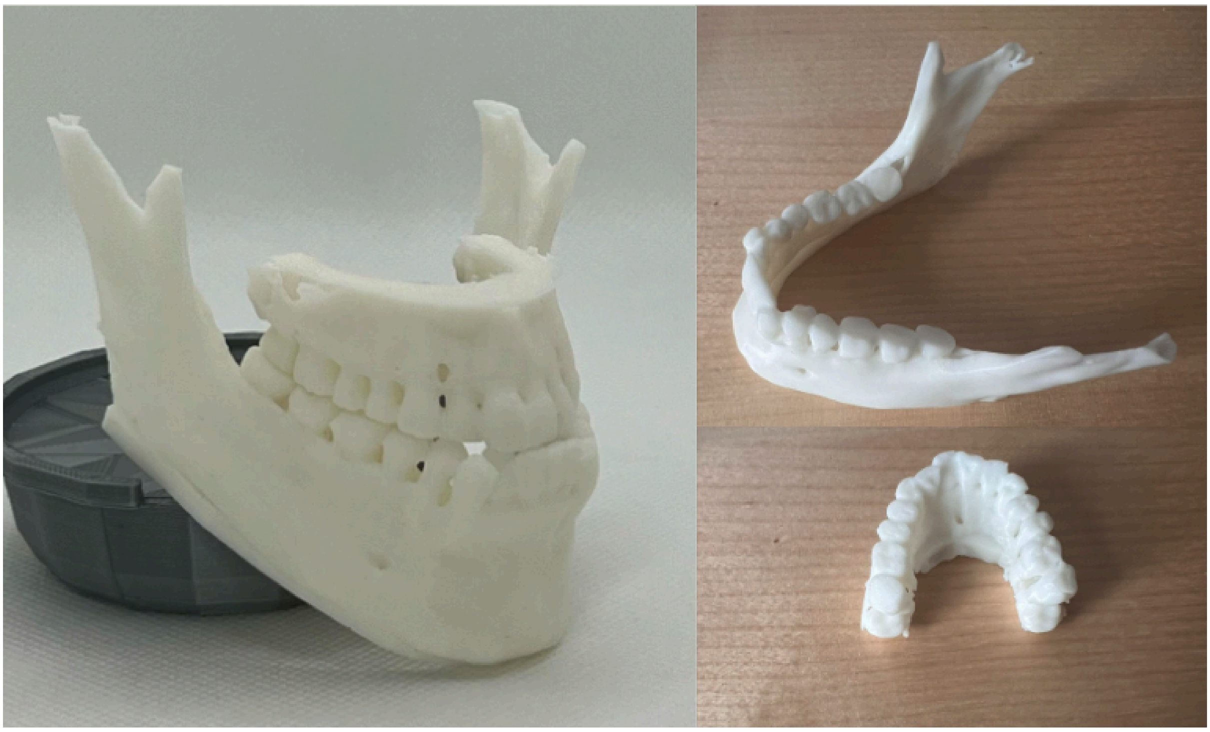

Figure 4.5 The final result of the human jaw pint. The bottom jaw can be separated from the upper teeth.

5. Discussion

The following sections provide more context to the results. They include challenges with the overall process, the impact of segmentation when compared to thresholding, the ability to create articulating joins in prints, and the impact of noise and pre-processing.

5.1 Challenges

Finding good data was challenging at times. A great example of this was the fox skull. This turned into a very good print for the jaw but the original CT scan was missing the very top part of the skull. This led to nothing connecting the front half and back half of the skull. Supports allowed us to print the entire skull together but it still wasn't a perfect print.

The printers at makerspace[3] created some limitations. They were used through the PrinterOS[1] software. This software had the limitation of only allowing normal supports (fig 5.1.1). Normal supports go straight up to attach to the underside of all overhangs. This means that a hollow model will be filled with support obscuring the fine details. A better option would be tree supports since the print could use supports that don't need to go into the internal structure of the print. Overall given our limitation, the manual supports created in blender acted closer to the tree supports and led to better prints.

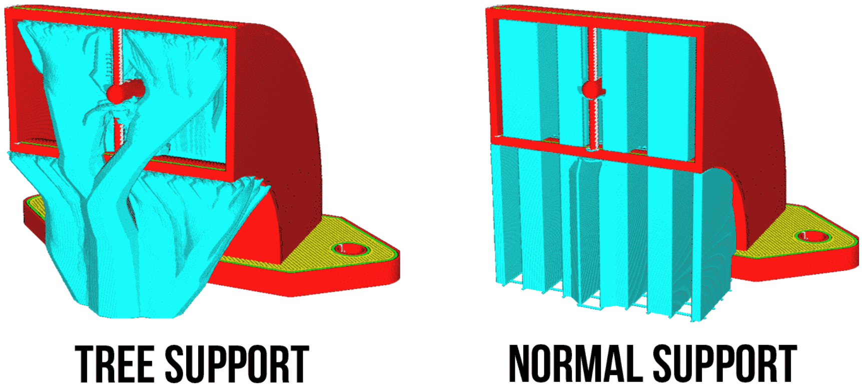

Figure 5.1.1 two different types of supports for 3D printing. The tree support provides structure but doesn't have to go into hollow space while the normal support fills all space below an overhang.

5.2 Impact of Segmenting

In this project, segmentation created STL files for an entire heart and the individual structures. This was completed using the segmentation editor in 3D Slicer. The process consisted of manually identifying sections of the DICOM image and assigning them to different segments of the heart, then defining their boundaries using the automatic segmentation feature.

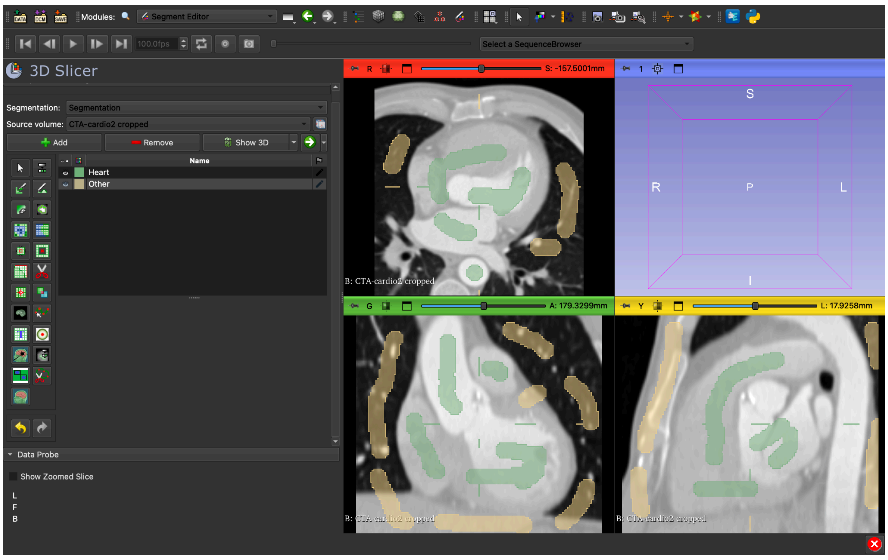

Figure 5.2.1 Defining the Heart segment and the Other segment using 3D Slicer's segment editor

Compared to thresholding, the process of segmentation takes much longer as it requires you to manually identify structures within several layers of the DICOM image then after the automatic segmentation is completed, you have to revisit the defined boundaries of the segments to ensure that they are defined correctly and accurately. The automatic segmentation tools in 3D Slicer greatly reduced the amount of time required to perform segmentation on the DICOM images, but it had limitations when defining boundaries within structures that had low levels of contrast, which meant that the boundaries in these areas had to be defined manually.

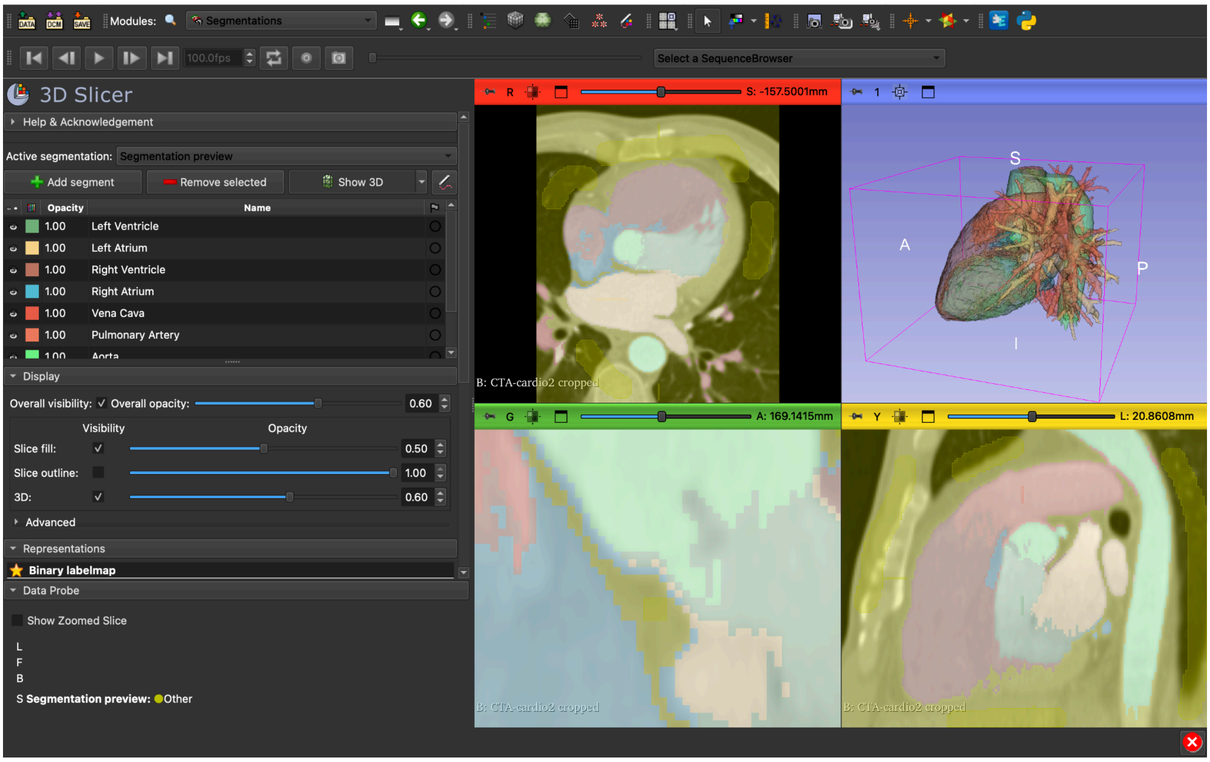

Figure 5.2.2 Adjusting the boundaries of the heart segments as part of the right atrium segment was defined within the right ventricle

5.3 Articulate Printing

Two prints were made to test articulate printing, the human jaw and the fox jaw. However, due to time and the limited CT scan data, we weren't able to add wire to create a hinge. This being said, the prints still showcased a moving jaw very well.

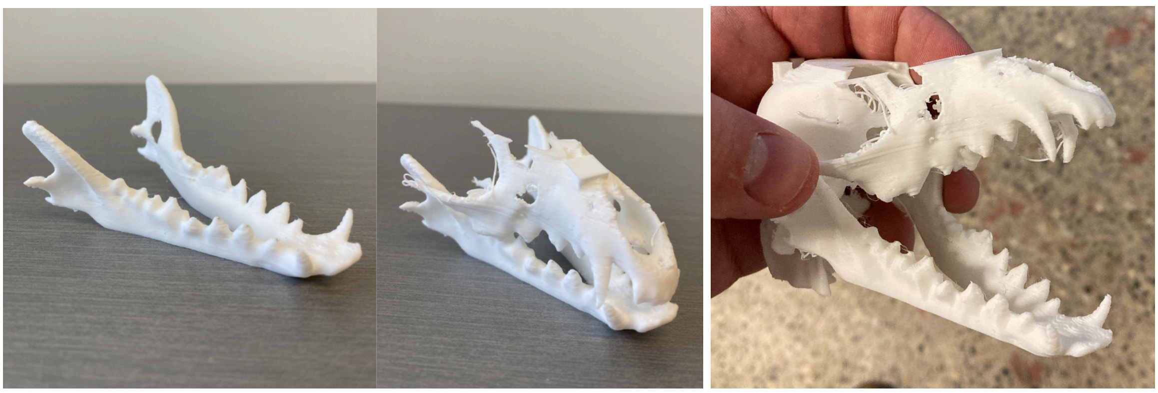

Figure 5.3.1. The fox skull has a jaw bone and the top of the skull. While the top part of the skull couldn't be printed well due to limitations of the original CT scan it did show the possibility of creating moveable prints.

Figure 5.3.2. The human jaw was the best print. The upper teeth and lower jaw fit together. Unfortunately, they couldn’t be connected with wire due to the limitations of the original CT not showing most of the skull.

5.4 Impact of Noise and Pre-Processing

To demonstrate the impact of DICOM image initial states on the final STL model, we will compare various initial conditions, including contrast levels, blurring, and noise variations, against a default rendering. Each condition's effect on model smoothness, contrast, and noise will be analyzed.

1. **Increasing Contrast:** It's worth noting remapping pixel values with window-level functions within 3D Slicer can make the component DICOMS more interpretable. It's still possible to generate a 3D image from high contrast data but it is more challenging, and generally at best, serves no purpose as performing techniques like histogram equalization to spread out the intensities seems not to improve tool performance. Likely because that process or something similar to it is implemented by 3D Slicer itself during the rendering process. At worst, it can be actively harmful when techniques such as adaptive histogram equalization are performed. This causes pixel intensities to be adjusted based on their immediate surroundings leading to more variation of intensity within pixels representing the same tissues causing a lot of distortion in the final result. This is shown in Figure 5.4.1:

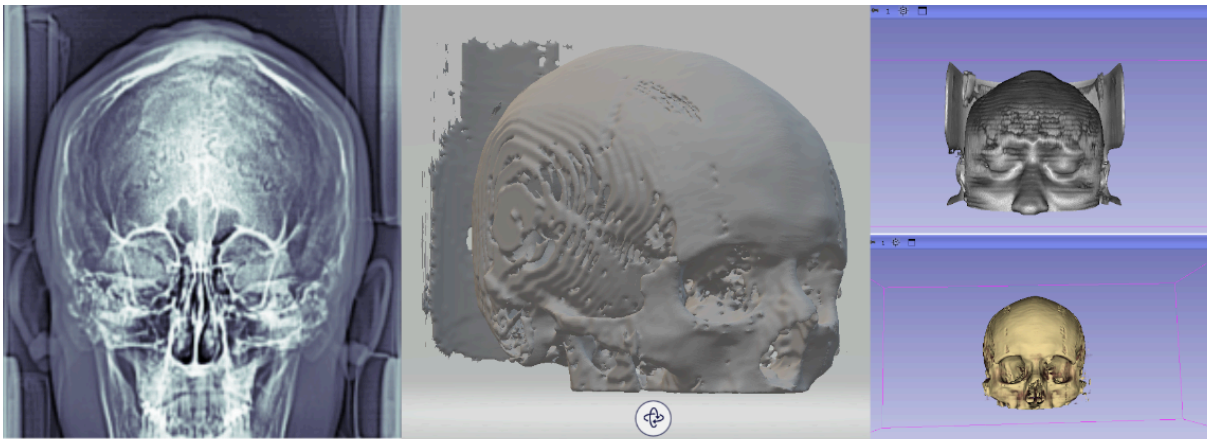

Figure 5.4.1. The distortion in the final result is because of the increase in variance in pixel intensity within a single tissue.

2. **Blurring the Image:** This was done with a Gaussian filter and averages the pixels in the kernel following a Gaussian distribution and having a smoothing or blurring effect on the

image. The results lead to a smoother 3D model as fewer of the rough imperfections or subtle variations translated over into the render. Applying blurring techniques in many cases may be of value when generating the STL.

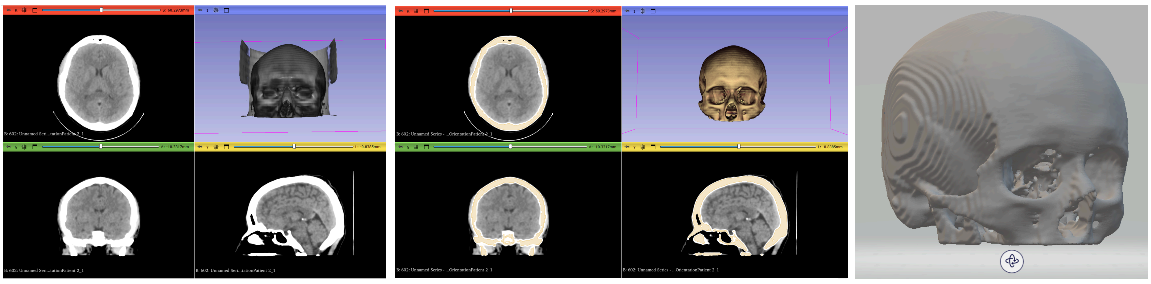

Figure 5.4.2. The STL file was a result of blurring the image.

3. **Adding Noise:** This included Gaussian noise and salt and pepper noise**.** Covering both unintended variations in pixel intensity and introduced speckles of black and white. These cases functionally cover most situations 3D Slicer may be confronted with. Gaussian noise had a very minimal effect on the result and even seemed to smooth out the model a little similar to Gaussian blur. Functionally the 2 effects are very different though, unlike the averaging effect from the Gaussian filter the noise is simply random variations in intensity with its probability density function following the normal distribution. Even with a great deal of noise, however, there seems to be enough distinction between tissues and 3D Slicer has little trouble generating the model. Salt and pepper on the other hand leads to variance within tissue pixels and affects the final result leading to the need for some manual post-processing after image generation and causing pitting in the skull.

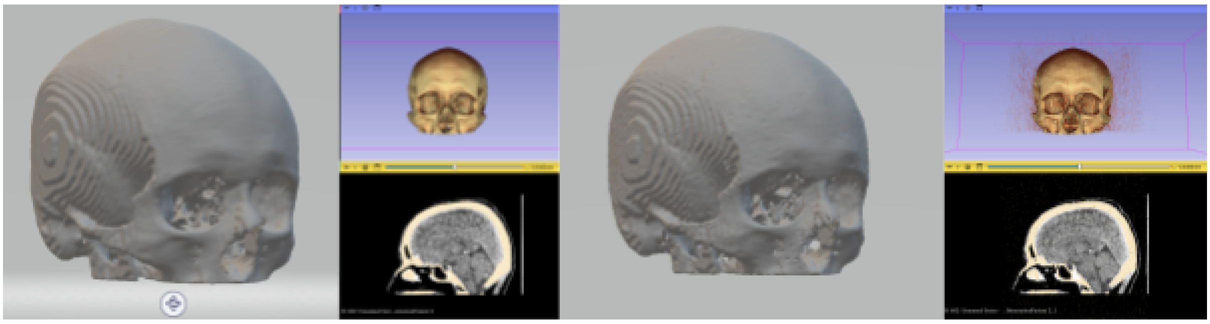

Figure 5.4.3. This shows the 3D renders from DICOMS with added Gaussian(left) and salt and pepper(right) noise. The results show minimal effect from Gaussian and minor impact from the salt and pepper.

6. Conclusion

Overall the process of creating and exploring the pipeline offered interesting results and helped develop methods to improve performance.

Thresholding is a fast method and leads to generally high-quality prints. Segmentation takes more time and does lead to higher quality prints but the difference in quality isn't as high as the time it takes to create it. Segmentation would be useful for isolating tissues from surrounding tissues but for bone, thresholding is generally the best method.

Having a printer that is reliable and offers tree support is essential to a streamlined and quality pipeline. This removed the need to add manual supports and can lead to quick quality prints.

Noise can negatively impact the print but Gaussian noise can improve the smoothness of the mesh and lead to better prints. Adjusting pixel values in DICOM images using window-level functions or histogram equalization techniques can enhance interpretability, but over-application, especially with adaptive methods, can distort tissue representation and potentially degrade the utility of 3D medical imaging.

Overall this project was successful and a pipeline can be used by anyone with access to the correct tools.

7. References

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