Proceedings of the 11th International Workshop on Innovative Simulation for Healthcare (IWISH), 004
19th International Multidisciplinary Modeling & Simulation Multiconference

2724-0029 © 2022 The Authors.
doi: 10.46354/i3m.2022.iwish.004

3D Printed Models of Heart/Aorta/Spine Assembly from CT Scan with IV Contrast: Maintaining Anatomical Correctness and Model Detail

Lori Lioce[1,*], Dietmar Moeller[2], Cooper Gunter[3], Trenton Kelsey[3], Gary Maddux[3] and Bernard Schroer[3]

[1]College of Nursing, University of Alabama in Huntsville, Huntsville AL 35899, USA
[2]Institute of Applied Stochastics and Operations, Clausthal University of Technology, Clausthal, Germany
[3]Systems Management and Production Center, University of Alabama in Huntsville, Huntsville AL 35899, USA

[*]Corresponding author. Email address: liocel@uah.edu

Abstract

This paper presents an analysis of the necessary parameters to assure an anatomically correct and detailed 3D printed model of a heart/aorta/spine assembly that was segmented from a CT (computed tomography) scan using 3DSlicer. The following parameters were analyzed: 1) CT scans with and without an IV contrast agent, 2) CT scan slice thickness of 3.75mm, 2.50mm and 0.98mm and 3) 3DSlicer threshold level, paint and grown from seeds, scissors and smoothing algorithm. Twenty models were segmented of the heart/aorta/spine assembly from a CT with an IV contrast of 2.50mm and 0.98mm. Six of these models were then printed on a Prusa i3 MK3. A CT scan with no IV contrast agent was ideal for developing 3D printed models of only the spine and not the heart since the bones were the only structures that were white and visible in the CT scan. An IV contrast agent in the CT scan was necessary for developing 3D printed models of organs such as the heart. The spine was also segmented from a CT with an IV contrast agent, however requiring the removal of many unwanted structures. The spine was denser than the heart and required a greater threshold value. The less dense heart required a lower threshold value. Therefore, the assembly was segmented into 1) a heart/aortic arch subassembly and 2) an aorta/spine subassembly. Important aspects of the 3D printed model were: 1) anatomical correctness, 2) correct scaling, 3) good modeling detail, and 4) relative location of the heart, aorta and spine and 5) ability for students to hold and view the models.

Keywords: 3D printing, simulator, human heart, 3DSlicer, CT scan.

1. Introduction

In recent years researchers and clinicians have demonstrated that patient specific heart models of different pathologies are useful in planning surgical and interventional procedures, in communicating with patients and in teaching students (Ciriza, etal, 2021). In a recent study (Ciriza, etal, 2021) a total of 138 heart models were segmented in a mean time of 136 minutes, printed and cleaned in a mean time of 13 hours and at a cost of $85 per model.

Ventola (2014) stated the use of 3D printed models for surgical training is preferred over training on cadavers. Cadavers often lack the appropriate pathology and provide more of a lesson in anatomy than a representation of a surgical patient.

The key features of medical imaging scans for 3D printing are: 1) presence of an IV (intravenous) contrast agent, 2) time of the IV contrast (15-20 seconds to flow into the heart, 30 seconds to flow into aorta and the best time to see tumors and organs, and after five minutes excreted into urine), 3) oral contrast for scan of abdomen, 4) slice thickness <1.25mm, 5) beam hardening artifact, and 6) reconstruction kernel (Itagaki, 2015).

CT scan slice thicknesses normally range from sub-millimeter to 5mm, depending on the anatomy being imaged and have a direct impact on the quality of 3D printed models. Thick slices will generate structures with a coarse appearance. Consequently, the 3D printed model will have a coarse appearance. With thin slices organs can be easier segmented for 3D printing (Ford and Decker, 2016).

The Systems Management and Production Center (SMAP) at the University of Alabama in Huntsville (UAH) has been supporting the College of Nursing (CoN) in the development of various trainers and simulators. One area has been the 3D printing of models of bones and organs from MRI (magnetic resonance imaging) and CT (computed tomography) scans. Some of these 3D printed models have been: 1) lumbar puncture and epidural trainers, 2) compression fractures and kyphoplasty repairs of L1 and T12 (Moeller, etal, 2021), 3) broken ribs and pneumothorax , and 4) organs including lungs, heart, liver, stomach, spleen, pancreas, kidneys, bladder and intestines (Lioce, etal, 2021).

These models were developed from MRI and CT scans by converting the medical images which were in a DICOM (Digital Imaging and COmmunications in Medicine) format to an STL file for 3D printing. Many of the STL files were downloaded from Embodi3D.com (Embodi3D, 2022). Embodi3D.com is a site where developers of medical STL files can place models for downloading, generally at no cost.

A requirement of the College of Nursing was for the 3D print models to be anatomically correct, good detail and in the correct location in the body. This paper presents the development of a heart/aorta/spine model that was segmented from a CT scan. Emphasis was on the parameters in 3DSlicer that are critical in segmenting a high quality 3D printed model. These parameters were 1) CT scans with and without an IV contrast, 2) CT scan slice thickness and 3) 3DSlicer threshold level, paint and grown from seeds, scissors and smoothing algorithm.

2. Methodology

A normal heart is commonly described as slightly larger than a fist. A normal adult heart is 13cm from base to apex, 9cm wide at the base and 6cm from anterior to posterior at its thickest point. Figure 1 shows the arteries, veins and valves of the heart.

3DSlicer is free, open source software for the three-dimensional visualization and analysis of medical images. Segmentation of images from a CT scan is a procedure to delineate regions in the image. Segmentation is a very common procedure in medical image computing and required for masking, visualization of structures, measuring volume and 3D printing. Segmentation may be performed manually by iterating through slices of an image; however, more often semi-automatic or automatic methods are used (3DSlicer, 2022).

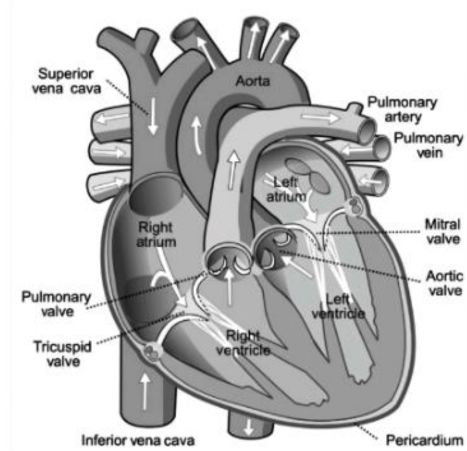

Figure 1. Human heart.

The 3DSlicer threshold range of -1024 to 3071 is similar to the Hounsfield Unit (HU) which makes up the gray scale in medical CT imaging. The HU unit is used by radiologists in the interpretation of CT images. It is a quantitative scale from -1024 (black) representing air to 3071 (white) representing the densest tissue in the human body. The HU scale is set around water measuring HU of zero. By altering the attenuation level (mid HU value) and range (extent of gray scale) at which the image is viewed, the tissue to be displayed can be determined (DenOtter and Schubert, 2021 and Materialise, 2022).

Attenuation is the reduction of the intensity of an x-ray as it transverses matter. The CT attenuation value is the radiodensity of a material and is expressed in HUs (Seishima, etal, 2014). Dense bones absorb much of the radiation while soft tissue (muscle, fat and organs) allow more of the x-rays to pass through them. As a result, bones appear white on the x-ray (HU +1000), soft tissue (organs) shows up shades of grey (HU -100 to +80) and air shows up black (HU lungs -500), and air -1000). The threshold HU values for bone are 226 minimum and 3071 maximum and for soft tissue are -700 minimum and 225 maximum (Chougule, 2017).

The threshold option in 3DSlicer segment editor is critical in creating 3D models of bones. A larger threshold will result in more bone detail and a loss in organ detail. A smaller threshold will result in more organ detail and less bone detail. Consequently, there must be a trade-off in threshold.

Figure 2 shows the 3DSlicer model of the full torso CT scan with an IV contrast agent, scan thickness of 2.50mm, a threshold of 96 and no smoothing. The extrusions and voids are the result of low attenuation levels, especially for the liver which is less dense and has an attenuation level between 55-65 HUs.

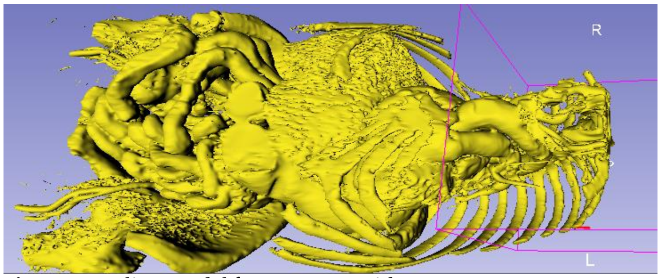

Figure 2. 3DSlicer model from CT scan with IV contrast agent.

The following CT scans were obtained from an 80 year old female, 62 inches tall and 135 pounds:

- CT1 with IV contrast agent that was reconstructed into scans of slice thicknesses 2.50mm and 0.98mm.
- CT2 with no IV contrast agent that was reconstructed into a scan of slice thickness of 3.50mm.

Table 1 lists the 3DSlicer models that were segmented from the CT scan with an IV contrast agent. The variables in the models were CT scan slice thickness, threshold option, paint and grow from seeds options and smoothing algorithm.

Several 3DSlicer models were segmented from the CT scan with no IV contrast and a slice thickness of 3.50mm. These models could be segmented quickly; however, the models only included bones and were unable to include any organs or the descending aorta. These models were not included in Table 1.

Table 1. 3DSlicer models from CT scan with IV contrast.

Model/ Figure (F)	Slice thickness	Threshold	Paint and grow from seeds	Scissors	Smoothing algorithm/ kernel
1Heart/aorta/spine	0.98mm	200	N	Y	None
2Heart/aorta/spineF3	0.98mm	143	N	Y	Median/closing/6.00mm
3Heart/aorta/spineF4	2.50mm	90	N	Y	None
4Heart/aorta/spineF5	2.50mm	90	N	Y	Closing/median/5.00mm
5Heart/aortaF6	0.98mm	118	N	Y	None
6Heart/aortaF7	0.98mm	118	N	Y	Median/closing/5.00mm
X3DBuilder heart/aortaF8	0.98mm	N	Y	Y	None
7Heart/aortaF9	0.98mm	N	Y	Y	None
8Heart/aortaF10	0.98mm	94	N	Y	None
9Heart/aorta	0.98mm	94	N	Y	Median/closing/5.00mm
10Heart/aortaF11	0.98mm	94	N	Y	Median/closing/7.00mm
11Heart/aortaF12	2.50mm	N	Y	Y	None
12Heart/aorta	2.50mm	N	Y	Y	Median/5.00mm
13Heart/aortaF13	2.50mm	N	Y	Y	Median/6.00mm
14Heart/aortaF14	2.50mm	48	N	Y	Median/5.00mm
15Heart/aortaF15	2.50mm	53	N	Y	Median/4.00mm
16Heart/aortaF16	2.50mm	96	N	Y	None
17Heart/aorta	2.50mm	96	N	Y	Median/closing/5.00mm
18Heart/aortaF17	2.50mm	96	N	Y	Median/closing/7.00mm
19Heart/aortaF18	2.50mm	121	N	Y	Median/closing/6.00mm
20Aorta/spineF19	2.50mm	96	N	Y	Median/3.00mm

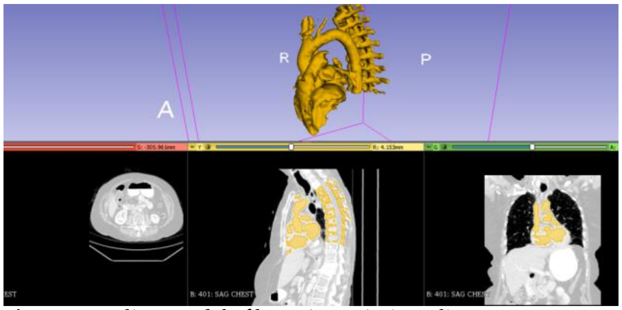

Figure 3. 3DSlicer model of heart/aorta/spine, slice=0.98, T=143, smoothing=6.00mm.

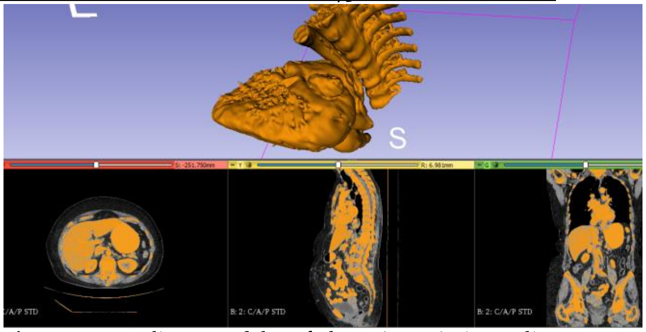

Figure 4. 3DSlicer models of heart/aorta/spine, slice=2.50mm, threshold=90, smoothing=none.

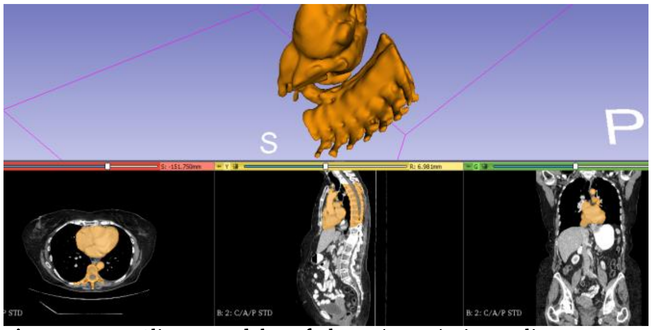

Figure 5. 3DSlicer models of heart/aorta/spine, slice=2.50mm, threshold=90, smoothing= 5.00mm.

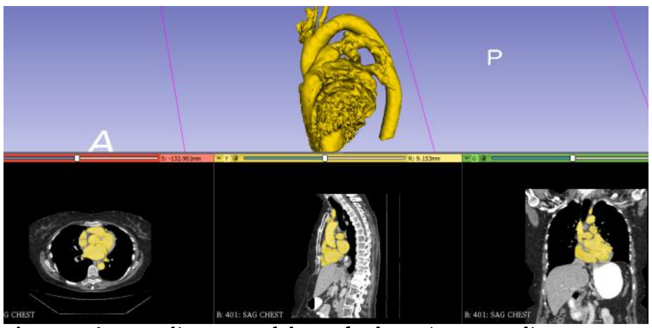

Figure 6. 3DSlicer models of heart/aorta, slice=0.98mm, threshold=118, smoothing=none.

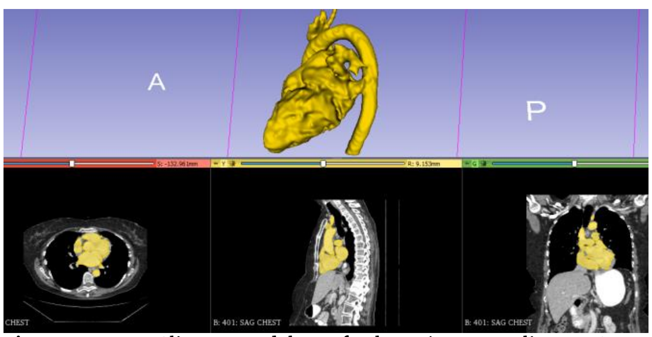

Figure 7. 3DSlicer models of heart/aorta, slice=0.98mm, threshold=118, smoothing= 5.00mm.

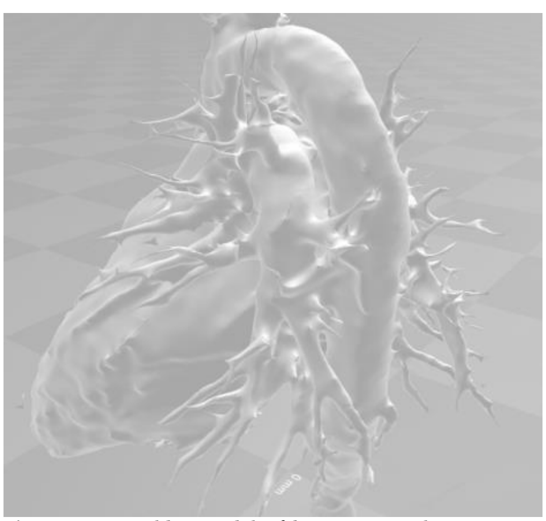

Figure 8. 3DBuilder model of heart/aorta, slice=0.98mm, paint and grow from seeds, smoothing=none.

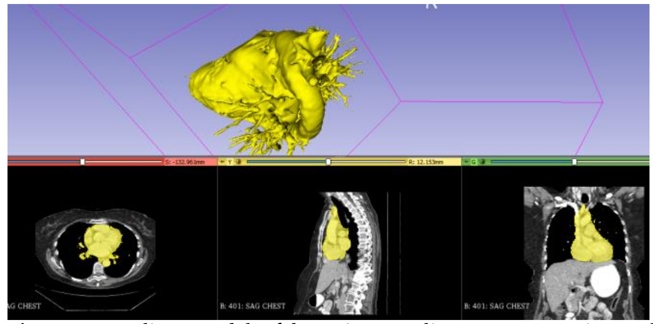

Figure 9. 3DSlicer model of heart/aorta, slice=0.98mm, paint and grow from seeds, smoothing=none.

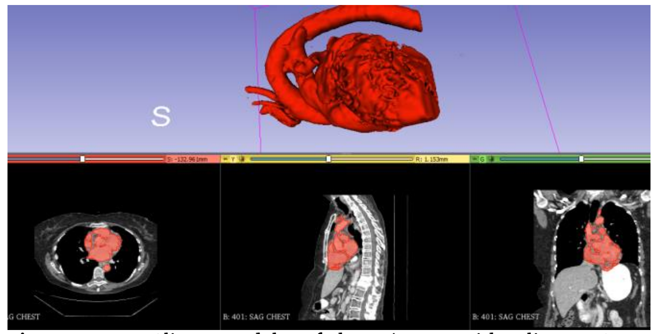

Figure 10. 3DSlicer models of heart/aorta with slice=0.98mm, threshold=94, smoothing=none.

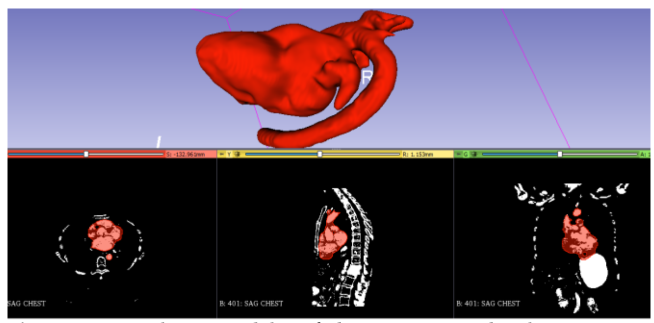

Figure 11. 3DSlicer models of heart/aorta with slice=0.98mm, threshold=94, smoothing=7.00mm.

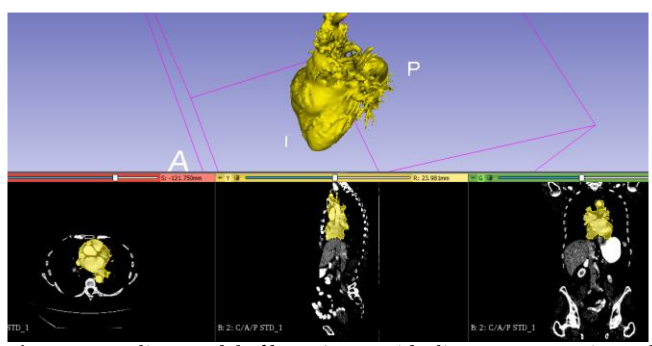

Figure 12. 3DSlicer model of heart/aorta with slice=2.50mm, paint and grow from seeds, smoothing=none.

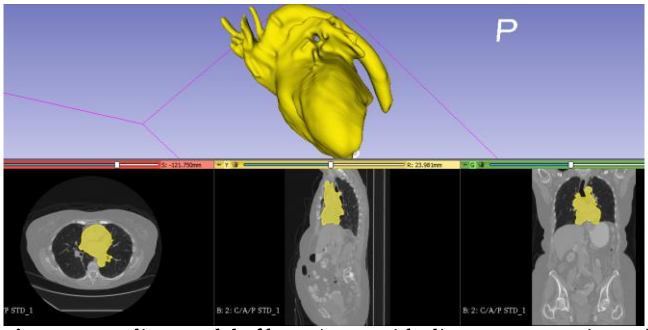

Figure 13. 3DSlicer model of heart/aorta with slice=2.50mm, paint and grow from seeds, smoothing= 6.00mm.

Figure 14. 3DSlicer models of heart/aorta, slice=2.50mm, threshold=48, smoothing=5.00mm.

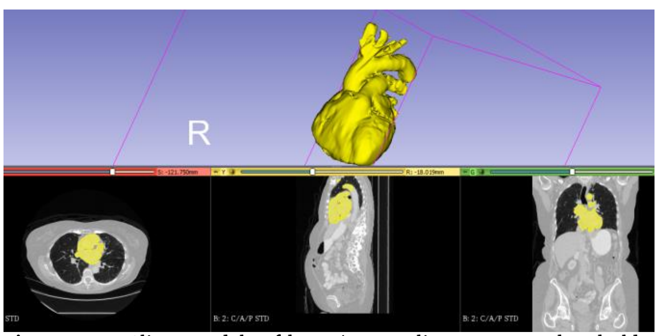

Figure 15. 3DSlicer models of heart/aorta, slice=2.50mm, threshold= 53, smoothing= 4.00mm.

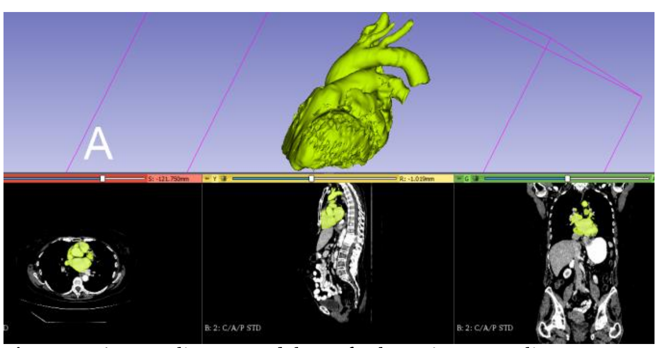

Figure 16. 3DSlicer models of heart/aorta, slice=2.50mm, threshold=96, smoothing=none.

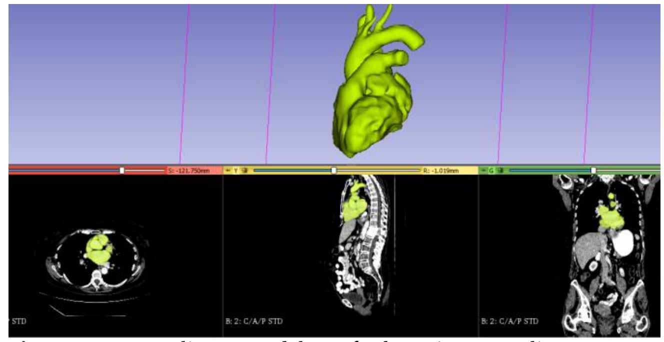

Figure 17. 3DSlicer models of heart/aorta, slice=2.50mm, threshold=96, smoothing= 7.00mm.

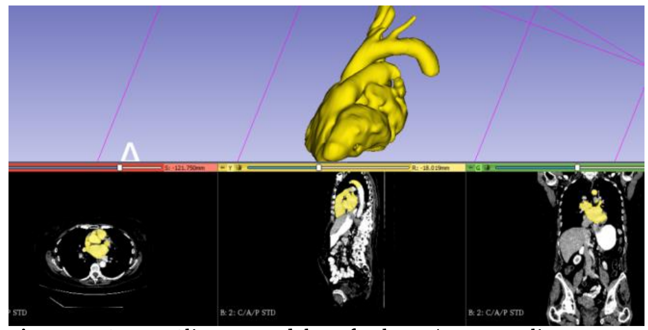

Figure 18. 3DSlicer model of heart/aorta, slice=2.50mm, threshold=121, smoothing=6.00mm.

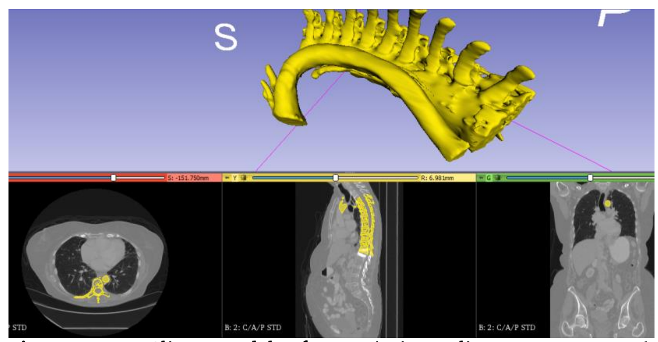

Figure 19. 3DSlicer model of aorta/spine, slice=2.50mm, T=96, smoothing=3.00mm.

3. Results and Discussion

Figure 20 shows the 3DSlicer model of the heart/aorta/spine segment from the CT scan with a slice thickness of 0.98mm, a threshold value of 200 and no smoothing. The voids in the vertebrae were the result of the high threshold value. Most of the organs had disappeared in the model.

Figure 21 shows the 3DSlicer model of the thoracic and lumbar spine segments from the CT slice thickness of 2.50mm, a threshold value of 876 and no smoothing. The two structures in the left of the figure show the bone cement (kyphoplasty) that were previously inserted into the compression fractures at the L1 and T12 vertebrae. The majority of the surrounding vertebrae did not print because of the high threshold.

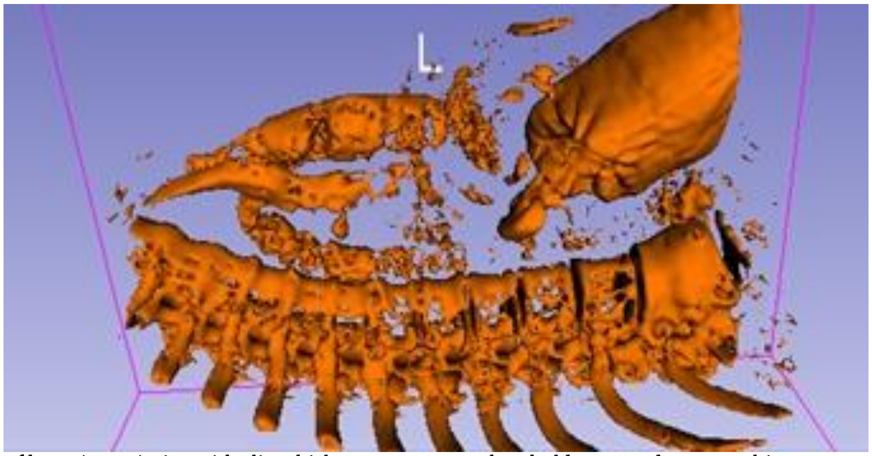

Figure 20. 3DSlicer model of heart/aorta/spine with slice thickness =0.98mm, threshold =200 and no smoothing.

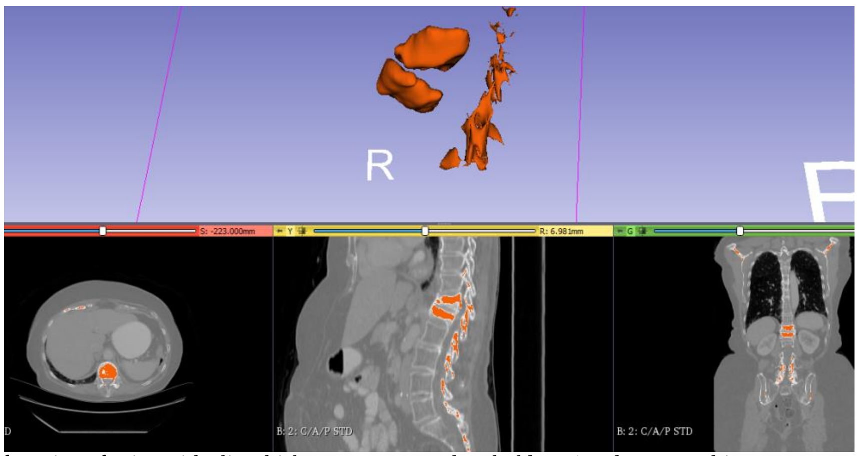

Figure 21.3DSlicer model of portion of spine with slice thickness=2.50mm, threshold=876 and no smoothing.

The heart was difficult to print because of the many voids and holes. Furthermore, a 3D printed model containing both the heart and spine was more difficult to print since the vertebrae are dense while the organs are less dense.

The threshold option in the 3DSlicer segment editor was critical in creating 3D models of the bones. A higher threshold resulted in more bone detail, more holes and no organs in the model. A lower threshold resulted is less bone detail, fewer holes and more organ detail. Consequently, there was trade-off between model details and holes. The paint and grow from seeds options in the 3DSlicer segment editor picked up much detail of the vessels into and from the heart. These small vessels could not be printed with the Prusa 3D printer.

The smoothing options in 3DSlicer made the segment boundaries smoother by removing extrusions and small details smaller that the specified kernel size while keeping the filling small holes. Specifically, the median option removed contours mostly unchanged. The closing option filled sharp corners and holes smaller than the specified kernel size.

A solution to the above issues was to use the 3DSlicer threshold option to segment the heart/aorta/spine segment into 1) a heart/aortic arch segment and 2) a descending aorta/spine segment. Smoothing algorithms were applied to the heart/aortic arch segment to reduce the detail and fill in the voids. Less smoothing was applied to the aorta/spine segment to retain more detail in the spine.

The two subassemblies were then connected together at the descending aorta. A sleeve was 3D printed and the two ends of the aorta inserted and fused to the sleeve.

Table 3 gives the 3D printed subassemblies. Model6 is identical to Model14 in Table 2. Likewise, Model3 is identical to Model20 in Table 2. The remaining models in Table 3 are slight variations to Models3 and 6.

Table 3. 3D printed subassemblies on Prusa i3 MK3.

Model	Slice thickness	Threshold	Paint and grow from seeds	Smoothing	Total PLA	PLA for supports	Print time/ Orientation
Heart/aortic arch subassembly							
1	0.98mm	57	N	6.00mm	243g	10%	20hrs
2	0.98mm	57	N	4.00mm			
3*	2.50mm	48	N	5.00mm			
4	2.50mm	108	N	5.00mm	221g	22%	31hrs
Aorta/ spine subassembly							
5	2.50mm	96	N	5.00mm	249g	32%	33hrs/Horizontal
6*	2.50mm	96	N	3.00mm	358g	44%	60hrs/Vertical

NOTES: Models 3 and 6 are listed in Table 2.
In-fill density 15% and layer thickness 0.15mm

Figure 22 shows the 3D printed model of the heart/aortic arch (Model1) with the aorta/spine (Model5). Figure 18 shows Model4 and Model6 subassemblies. The heart in Figure 23 has more detail especially the aorta and pulmonary arteries. The visible vessels rising from the heart were: 1) aortic arch with the brachiocephalic trunk, left carotid artery and left subclavian artery, 2) superior vena cava, 3) left pulmonary artery and 4) the inferior vena cava at the bottom of the heart (Figure 1).

The average heart measurements were 131mm in height (base to apex), 127mm wide at the base and 94mm from anterior to posterior at its thickest point. This is slightly larger than normal. The outside diameter of the descending aorta was 21mm which was within the range of the normal value.

Figure 22. 3D printed model of heart/aortic arch (Model1) and aorta/spine (Model5).

Figure 23. 3D printed model heart/aortic arch (Model4) and aorta/spine (Model6).

4. Conclusions

CT scans with no IV contrast agent were ideal for developing 3D printed models of the spine and not the heart since the bones were the only structures that were white and visible in the CT scan. CT scans with an IV contrast agent were necessary for developing 3D printed models of organs such as the heart. The IV contrast enhanced the heart on the CT scan and assisted in segmentation. The spine was also segmented from the CT with an IV contrast agent, however requiring the removal of many unwanted structures.

Another model of the spine was printed from the CT scan with no IV contrast agent and a slice thickness of 3.75mm. The model was easily and rapidly segmented. However, without the IV contrast the aorta did not appear on the CT scan and could not be printed. This highlights the tradeoffs in printing models with and without an IV contrast agent.

The spine was denser than the heart and required a greater threshold value. The less dense heart required a lower threshold value. Therefore, the heart/aorta/spine assembly was segmented into two segments, a heart and aortic arch subassembly and an aorta and spine subassembly. Smoothing algorithms were applied to both segments. However, a larger kernel resulted in less detail in the 3D printed model. The smoothing of the heart filled in the voids at the expense of more detail for the arteries rising from the aortic arch, the superior vena cava and the pulmonary artery.

The difficulty in segmenting the heart using the 3DSlicer threshold option, even a CT with an IV contrast, was to determine the edge of the heart from the nearby organs such as the liver. Once the threshold level has been selected the scissors option was used to cut away unwanted structures.

The scissors option was very time consuming and required constantly rotating the model. The paint and grow from seed was another option to segment the heart. Considerable effort was necessary to use the scissors options to remove the detail arteries rising from the heart.

Very little difference was noticeable in the finished heart/aorta/spine assembly models. The three major arteries rising from the aortic arch (brachiocephalic trunk, left carotid artery and left subclavian artery), the superior vena cava, the inferior vena cava and the left pulmonary artery were all recognizable in the 3D printed models. Important aspects of the 3D printed model were: 1) anatomically correct, 2) correct scale of the heart and spine, 3) good model detail, and 4) relative location of the heart, aorta and spine and 5) ability for students to hold and view the models.

The heart/aorta/spine assembly has been included into the anatomy training for nursing students in the College of Nursing. With 3DBuilder nursing students can view and rotate and enlarge the model on their own computer. With the 3D printed models students can hold and view the models.

Acknowledgements

This project was supported by The University of Alabama in Huntsville (UAH) Systems Management and Production Center and The UAH College of Nursing.

References

Chougule, V., Mulay, A., and Ahuja, B. (2017). Clinical case study: spine modeling for minimum invasive spine surgeries using rapid prototyping, *Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN10)*, Indian Institute of Technology Madras, Chennai-600036 India, Dec.

Ciriza, G., etal (2021). Affordable three-dimensional printed heart models, *Frontier in Cardiovascular Medicine*, 8, published online Jun, www.ncbi.nim.nih.gov

DenOtter, TD and Schubert, J. (2012). Hounsfield Unit, StatPearl (Internet), Treasure Island FL, *Statpearl Publishing*, Jan.

Ford, J. and Decker, S. (2016). Computed tomography slice thickness and its effects on three dimensional reconstruction anatomical structures, *Journal of Forensic Radiology and Imaging*, 4: 43-46, Mar.

Itagaki, M. (2015). Choosing the best medical imaging scan to create a 3D printed model, *Embodi3D*, www.embodi3D.com, May.

Lioce, L., Tidwell, S., Gunter, C., Myler, M., Moeller, D., Maddux, G., and Schroer, B. (2021). Development of full-scale 3D printed model of human body with organs and associated arteries for the training of nursing students, *Proceedings 14th International Conference of Education, Research and Innovation (ICERI2021)*, Seville Spain, Nov 8-10.

Moeller, D., Lioce, L., Gunter, C., Maddux, G., Fogle, I., Goddard, N., and Schroer, B. (2021). An analysis of compression fractures and kyphoplasty repairs to the lumbar and thoracic spine segments: using computer simulation and 3D printed models, *Proceedings 15th International Technology, Education and Development Conference (INTED2021)*, Valencia Spain, Mar 8-10.

Materialise (2022). What are Hounsfield Units (HU). *www.materialise.com*.

Seishima, R., Okabayashi, K., Hasegawa, H., Tsuruta, M., Hoshino, H., Yamada, T., and Kitagawa, Y. (2015). Computed tomography attenuation values of ascites are helpful to predict perforation site, *World Journal of Gastroenterology*, published on-line, 21(5): 2573-79, Feb 7.

Ventola, C. (2014). Medical applications for 3D printing current and projected uses, *Pharmacy and Therapeutics*, 39(10): 704-11, Oct.

Viglino, D., Martin, M., Almeras, N., Despres, J., Coxson, H., Pepin, J., Vivodtzev, I., and Maltais, F. (2019). Low liver density is linked to cardiovascular comorbidity in COPD: an ECLIPSE cohert analysis, *International Journal of Chronic Obstructive Pulmonary Disease*, 14: 3053-61, published on-line Dec 31.

3DSlicer (2022). Basic concepts, *3DSlicer*, www.slicer.org.