



Data Segmentation for Medical 3D Printing

The purpose of this document is to enable a user to process, segment and successfully 3D print data acquired via 3D medical imaging. It includes information about the techniques and best practices for medical image acquisition and the software required to convert images into a 3D printable file.

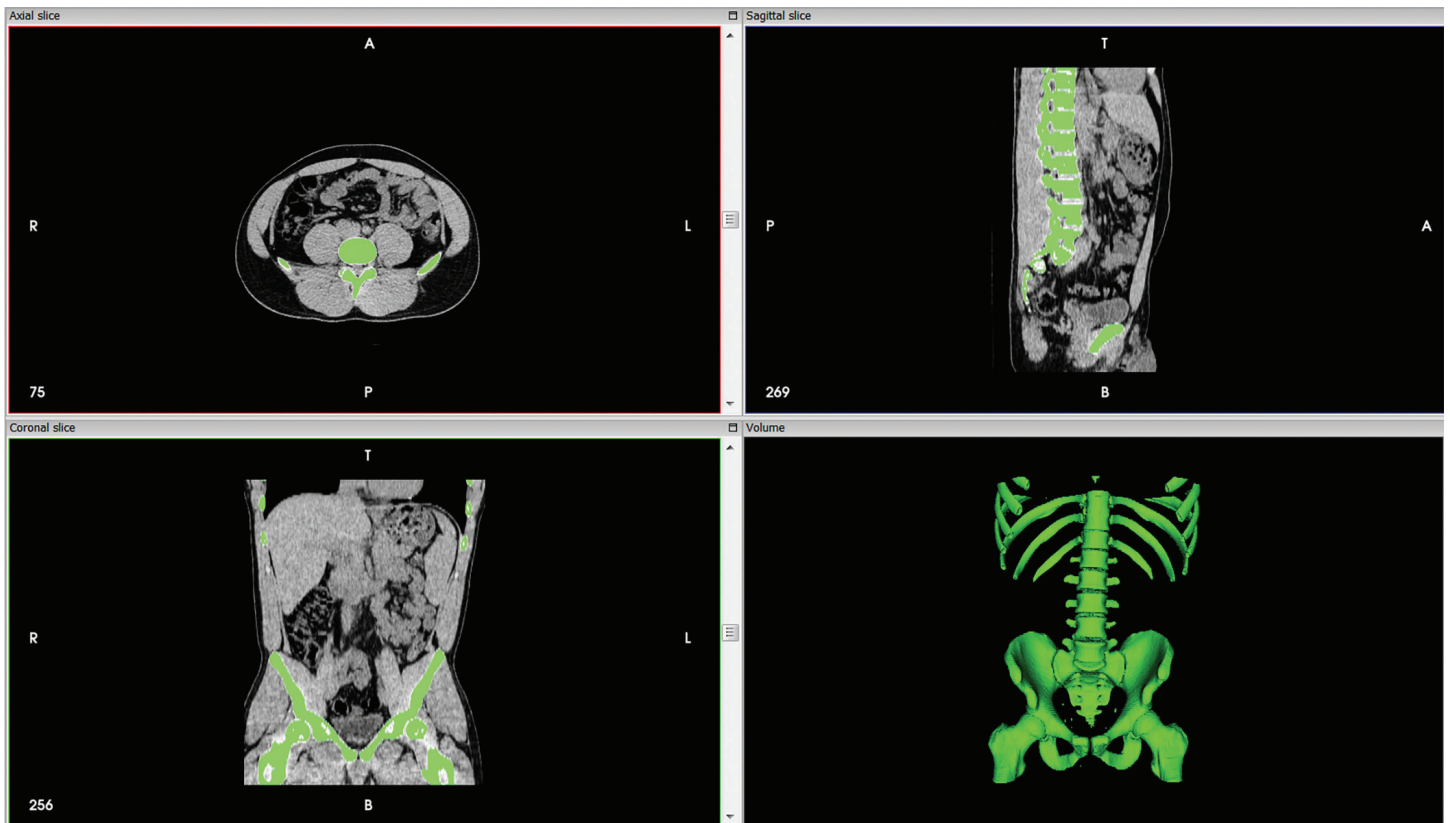


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1. Process Overview

Anatomical models have several medical applications — from patient-specific models used to plan and optimize surgical approaches, to sophisticated training simulators for physician education, to clinically relevant models to verify and validate new medical devices. Since 3D printing requires no tooling and can reproduce complex structures with no added cost, it is a natural match for such applications. However, developing these models can be a challenge due to the complexity and irregularity of human anatomy.

One starting point is to use data readily available in the form of patient imaging scans generated by non-invasive MRI, CT or 3D ultrasound testing. Using this information, model designers can recreate the complexity of any disease, abnormal anatomy or variation. The first challenge with this approach is to isolate the anatomy of interest (referred to as segmentation) and convert it into a file format readable by CAD and 3D printing software.

A variety of commercial, freeware, and open-source solutions are available to perform these steps. This document describes the approach using InVesalius (freeware) and Vitrea (commercial software) as an example, but the process can be replicated with many solutions.

Commonly used software for segmentation:

- InVesalius: free software to convert DICOM images to STL files.
<http://svn.softwarepublico.gov.br/trac/invesalius>
- OsiriX Lite: Free software to view and annotate DICOM files.
<http://www.osirix-viewer.com/osirix/osirix-md/download-osirix-lite/>
- Vitrea Advanced Visualization: Commercial software offered by Vital Images, a Toshiba company that automates many segmentation activities.
<http://www.toshiba-medical.eu/eu/healthcare-it/vital-solutions/vitrea-advanced/>
- Mimics inPrint: Commercial segmentation software with semi-automated tools and modules for orthopedics and cardiology. It is also used as pre-operative software for simulating and evaluating surgical treatment options and is a CE-marked medical device.
<http://hospital.materialise.com/medical-3D-Printing-mimics-inprint>

2. Obtain the DICOM Data

Digital Imaging and Communications in Medicine (DICOM) is the international standard for medical imaging, including its storage, communication, transmission, file format and handling. Doctors will provide DICOM data upon request. All modern medical imaging devices that support the DICOM standard will export files that are readable by all the viewers and editing software discussed in this document.

Since the human body is very complex and highly variable, several imaging modalities are typically used for patient care. They vary in their data representation and image intensity representation. A health care professional will normally use one or more of the following modalities, based on the clinical question and availability. For example, because ultrasound equipment is more widely available in smaller hospitals, they might use it for initial screening and refer the patient to a larger center for an MRI test if further diagnostics are necessary.

Since 3D printing creates mechanical structures, it is important to understand what the image intensity represents. Image-related terms such as pixels, intensity and contrast will be discussed later in this document. Usually, the DICOM output provides a series of 2D images (slices) that are then reconstructed in 3D, either for viewing on a screen or for physical reconstruction (such as 3D printing).

2.1. CT (computed tomography)

This method uses a series of X-rays taken from different angles, to be reconstructed later. The pixel value represents the radio density of the tissue (the amount of X-ray that the tissue blocks) and the brightness represents a Hounsfield unit. Generally, brighter areas are denser than dark areas. For example, a bone is brighter than the surrounding connective tissues. This method is typically fast and used for evaluating the structure of various tissues in the body. The main drawback is inability to differentiate structures with similar densities such as muscles and tendons.

2.2. CTA (computed tomography angiography)

In this method, the patient receives an injection with a contrast agent, which appears as a brighter region representing blood flow. As the contrast agent travels through the cardiovascular system, it reveals abnormalities such as blood clots and aneurysms.

2.3. MRI (magnetic resonance imaging)

This method uses a strong magnetic field that excites hydrogen atoms in the body, causing them to emit radio frequency detected by the scanner. Since hydrogen atoms exist in humans in large quantities, particularly in water and fat, this method is excellent for demonstrating small differences between soft structures in the body. MRI is popular for testing pathologies in the brain and muscular tissues. One major advantage is that it does not expose the subject to potentially harmful radiation.

2.4. MRA (magnetic resonance angiography)

With MRA a contrast agent is injected into the patient. Brighter regions will appear where there is blood flow. This method is typically used to diagnose issues such as strokes in the brain's vascular system.

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2.5. PET (positron emission tomography)

With PET a radioactive material is “attached” to a biologically active molecule (typically a type of glucose) to show where there are metabolically active regions (such as tumors). This method will sometimes be used with CT/MRI and fused together.

2.6. 3D ultrasound

In this method, high-frequency sound waves are sent into the body at different angles. As they are reflected back, the receiving device interprets the returned waves to produce a live 3D image of the internal organs. Ultrasound images are very good at showing the boundaries between liquid-filled organs and solid organs but typically provide inferior resolution compared with other imaging techniques.

Modality	Demonstrates	Used for	Advantage	Disadvantage
CT	Density	Bones, soft tissue	Quick, high resolution	Not best for soft tissues, radiation exposure
CTA	Blood flow	Cardiovascular conditions	Shows small blood vessels	Does not show surrounding tissue
MRI	Water and fat	Soft tissues, muscles, brain tissue	No radiation; high resolution	Does not show surrounding tissue
MRA	Blood flow	Cardiovascular conditions	Shows small blood vessels	Does not show surrounding tissue
PET	Glucose intake	Tumors, lymphatic conditions	Shows activity in tumors	Does not show surrounding tissue
3D ultrasound	Boundary between organs	Pregnancy related tests, initial analysis	Cheap, live image, no radiation	Low resolution; does not show internal structures

3. Medical Viewers

Dozens of software solutions are available to display DICOM images. They vary from free-to-use open-source software to enterprise-level solutions with FDA clearance. This document will feature only a small subset of these solutions, which should be enough to cover most uses and interactions with medical imaging specialists.

Common software solutions

3.1. OsiriX

OsiriX is a widely used DICOM viewer and features a strong visualization engine that allows editing. Registration is required to download the free version. The website features free DICOM examples, which may be used in other viewers.

3.2. InVesalius

InVesalius is a free software supported by the Brazilian government. It can create STL files using thresholding techniques (see section 4.1.2),

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and features a strong community with step-by-step guides. It performs well segmenting bone but is less consistent when segmenting soft-tissue structures.

3.3. ITK-SNAP

ITK-SNAP is a software application used to segment structures in 3D medical images. It is the product of a collaboration between the universities of Pennsylvania and Utah, whose vision was to create a segmentation tool that would be easy to learn and use. ITK-SNAP is free, open-source, and multi-platform. It provides semi-automated segmentation using active contour methods.

3.4. Mimics by Materialise

3D printing software company Materialise developed Mimics specifically for medical image processing. It is considered the industry standard among large medical centers and features a strong segmentation and STL-creation engine.

3.5. Mimics InPrint

Mimics InPrint is a relatively simple-to-use version of Mimics, targeted at enabling doctors to create 3D models with greater ease and speed. It features both thresholding and active contour segmentation modules.

3.6. Vital Vitrea

Vitrea is a medical diagnostic system that allows the processing, review, analysis, communication and media interchange of multi-dimensional digital images acquired from a variety of imaging devices. Vitrea provides the ability to review digital images from original DICOM data for multiple modalities.

Table 1: Software For Viewing DICOM Images

NAME	DICOM IMPORT	3D VISUALIZATION	STL CREATION	STL FIXING	STL EDITING	FDA CLEARANCE*	THRESHOLDING	AUTO SEGMENTATION	FREE
OsiriX	✓	✓							✓
InVesalius	✓	✓	✓	✓			✓	✓	✓
ITK SNAP	✓	✓	✓				✓	✓	✓
Mimics	✓	✓	✓	✓	✓	✓	✓	✓	
Mimics InPrint	✓	✓	✓	✓	✓	✓	✓	✓	
Vitrea	✓	✓	✓			✓	✓	✓	
Seg3D	✓	✓	✓				✓	✓	✓
3Dslicer	✓	✓	✓				✓		✓
DeVIDE	✓	✓	✓				✓	✓	✓
TurtleSeg	✓		✓						✓

* Check with the software manufacturer's labeling to determine specific FDA clearances.

4. Segmentation Explained

Since medical imaging techniques show the entire body, including the surrounding tissues, the data set must be segmented. This means any undesired data is removed and only the relevant portions remain. Several techniques can accomplish this; this guide shows the two primary methods that you can experiment with using free tools.

3D printing requires exporting one or more (if using a multi-material platform) closed surfaces as an STL assembly. This is done by marking the relevant data and discarding the surrounding data. In Figure 1 both the skin and bone are shown in the 3D view. We would like to keep only the bone, shown in Figure 2.

The two techniques described below vary in their approach to segmentation, and are the most widely used techniques.

4.1. Segmentation techniques

4.1.1. Automatic segmentation

This family of techniques is typically found in commercial segmentation software such as Vital Images Vitrea Advanced Visualization, and uses advanced algorithms to automatically or semi-automatically separate specific organs from the surrounding tissues. Some methods used for automatic segmentation are: region growing, region shell, digital subtraction and seed growing.

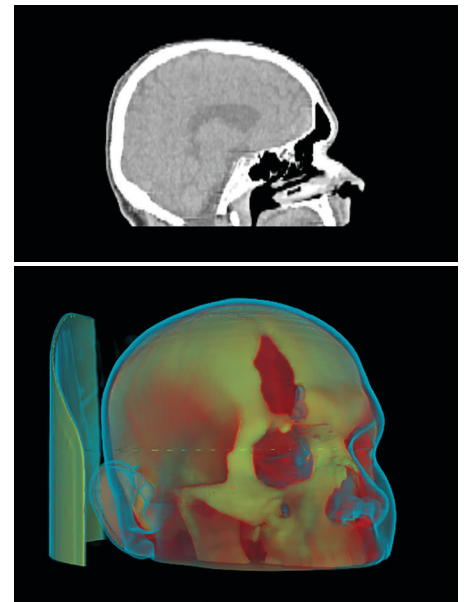


Fig 1: A scan of a human head showing tissue and bone.

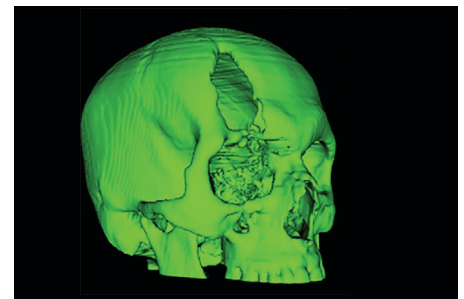


Fig 2: Isolated bone is the objective of this segmentation exercise.

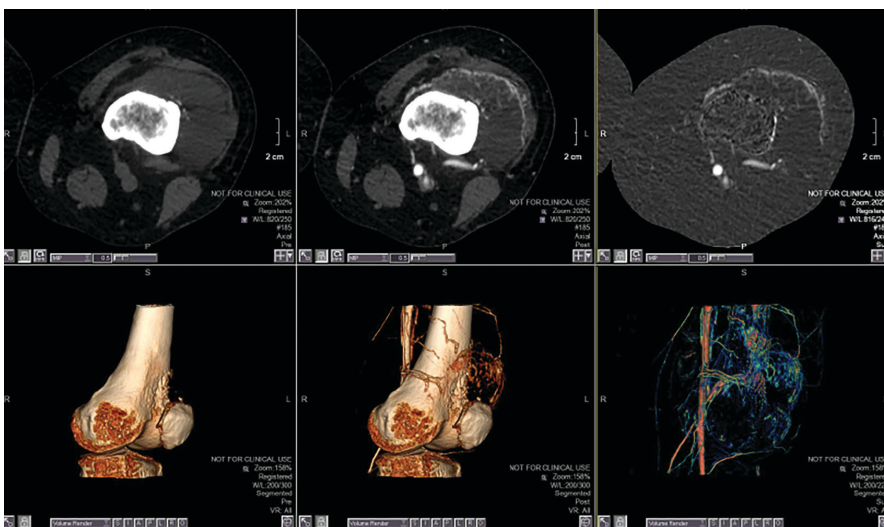


Figure 3: Digital subtraction of tumor vessels. From left to right: Non-contrast CT, contrast-enhanced CT and new-subtracted 3D images. Image courtesy of Vital Images.

Auto-segmentation software often uses predefined algorithms based on the anatomy of interest, allowing the user to select what region to segment. The 3D models derive from both automated and interactive segmentation tools. These models can combine multiple anatomic regions and pathologies. They are exported as STL files for further refinement and 3D printing. The segmentation of 3D models

can be performed using several registered 3D volumes such as an arterial phase volume showing the arteries and a venous phase volume showing the veins. Consult the segmentation software's documentation for a detailed workflow on how to achieve adequate results.

4.1.2 Thresholding

Thresholding is typically used in scans where a certain anatomy has a very distinct set of values (a high contrast). Keeping only certain values of the medical image lets us visualize a specific part of the body (only bones, for example). Using the skull example above, we'd like to isolate only the bone data.

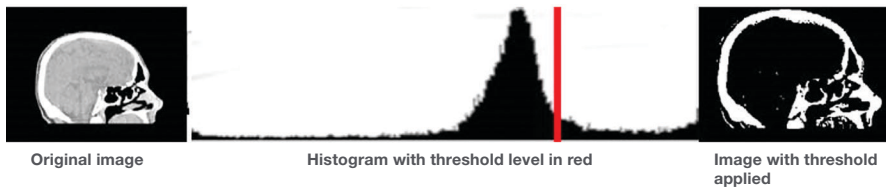


Figure 4: Using thresholding to isolate the bone.

4.1.2.1 Remembering that in CT images the pixel value represents the density, keeping only the brighter pixels leaves only the bone. The image in Figure 4 had pixel values ranging from -1,024 to 3,000. As seen in Figure 5, choosing this range highlights the entire image, preventing the extraction of only the bone.

However, choosing only pixels valued 200 and up (200 to 3033), only the bone is left marked (Figure 6).

One disadvantage of this method is that it does not consider the shape of the segmented region. If only the brain tissue in Figure 7 is marked, the skin and sinus tissue are still visible, as they are approximately the same density (Figure 7).

5. Contrast and Windowing

A scanned medical image set usually contains a large range of data. For example, Figure 8 has values ranging from -2,048 to 1,600. If the entire range is shown, all tissues scanned such as muscle, fat and hard cortical bone will appear. To visualize more subtle differences in specific organs or tissues, change how the image is displayed.



Figure 5: Choosing the entire range of pixel values highlights the entire image.

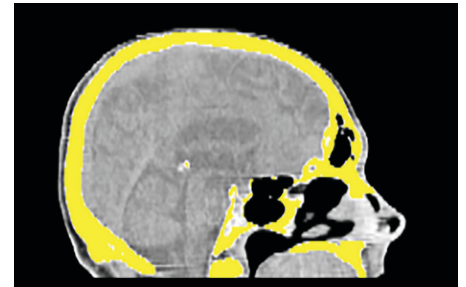


Figure 6: Appropriate pixel selection isolates the bone.

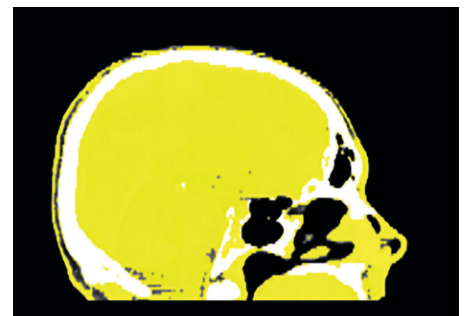


Figure 7: Tissues of similar density are shown.

To enhance the visualization, indicate the intensity of the data you are looking for, and how much of it you want to see (Figure 8).

Typical parameters that appear in DICOM segmentation/visualization software control the appearance of such models:

- White level: indicates which level is rendered on screen as white.
- Window size: indicates how much of the actual values are shown on-screen. Every value outside the window will be either fully black or fully white.

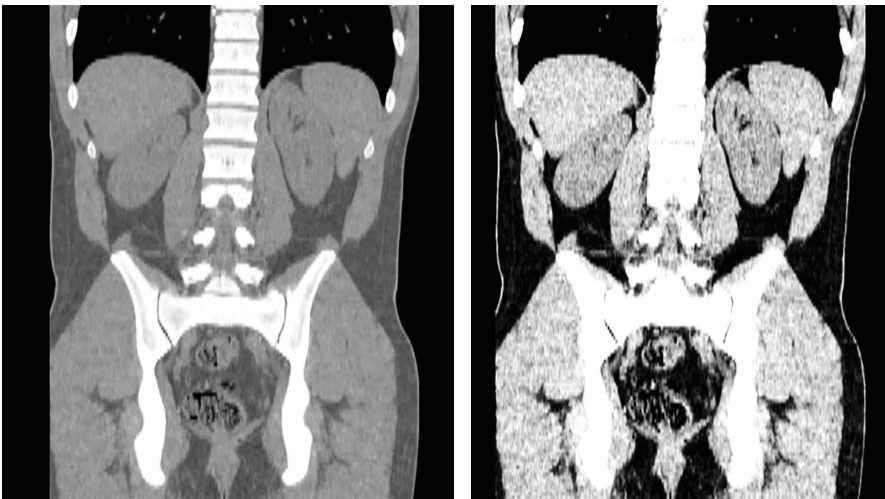


Figure 9: (Left) white level 0, window size 1000; (right) white level 0, window size 500.

Start by finding the value of the tissue you are trying to visualize and set the window size to the smallest possible value that clearly shows the boundaries.

6. Preparation for 3D Printing and Data Optimization

6.1. Slice height on DICOM explained

To reduce the exposure to potentially harmful radiation and minimize scan time, medical imaging experts use various scanning protocols. One major factor that varies between scans is the slice height. This represents the space, in millimeters, between two images in the DICOM set. Typical values are 0.3-0.7 mm (300-700 μ). Considering that PolyJet™ 3D printers can build with slice heights of 16-30 μ , the data will need to be optimized before 3D printing.

6.2. Smoothing

Smoothing takes several slices from the DICOM data and creates additional slices between them for 3D printing. Figure 11 shows this process using Materialise Magics.

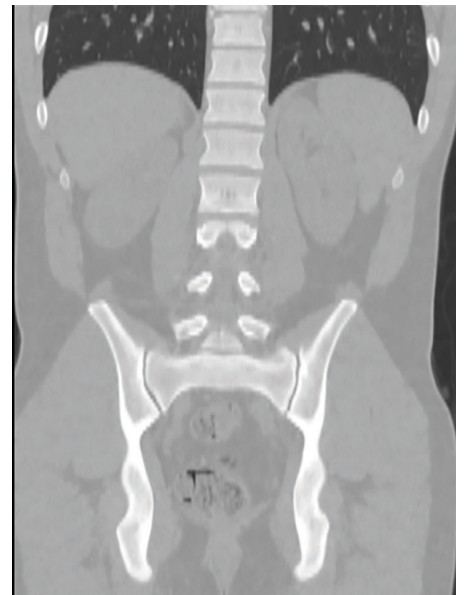


Figure 8: In this abdominal CT we can easily visualize the bones and the air in the lungs. The soft tissues are hard to distinguish from one another.

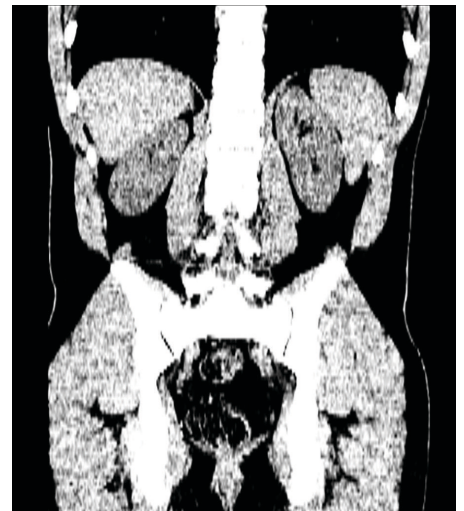


Figure 10: White level of 30 and window size of 150 clearly shows the outline of kidneys, while the bones are saturated.

7. Data Acquisition Best Practices

The final product (such as a 3D printed surgical planning model) depends on the quality of the original data. Image resolution, the use of contrast to enhance the anatomy, and software sophistication can all significantly affect the final product. Follow these recommendations to acquire the best data.

- Good CT, MR and 3D X-ray datasets improve the final result and decrease the time to prepare 3D models. Thin-sliced CT datasets, good contrast enhancement and low-noise images give the best results.
- Dual phase or multi-phase CT datasets allow simpler segmentation using digital subtraction or multi-phase fusion. 3D MRI high-resolution datasets also give better results than thick-slice MR series.
- To some extent, Vitrea Software’s 3D noise reduction (called SPD) can be used on-the-fly to improve the segmentation of a very noisy dataset.
- In a challenging multiple-part segmentation, start segmenting the well contrasted parts (for example, cardiac blood pool, metal implants) then the low-contrast parts (myocardium, low-density bones).

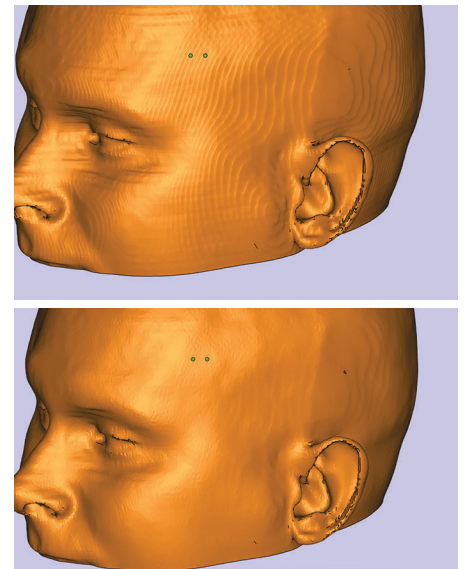


Figure 11: Top, the skin surface is taken from CT with a slice height of 0.625 mm; stair-stepping is pronounced enough to appear in the 3D printed model. Bottom, after global smoothing with 85% strength in Magics.

8. 3D Printing Best Practices

3D printing, (also known as additive manufacturing), can be done on a variety of technologies. Primarily, Stratasys employs FDM® and PolyJet. Each possesses strengths and weaknesses when it comes to medical models. FDM lets you 3D print parts in a broad range of well-tested plastics. PolyJet offers a wide range of colors, mechanical properties and the ability to print in flexible and translucent materials. Table 2 shows these two technologies and appropriate material choices for medical modeling.

Table 2: 3D Printing Technology And Material Selection

Technology	Materials	Sterilization methods	Biocompatible	Flexible	Multi-material	Translucent	Full color
FDM	Thermoplastic	EtO Gamma Autoclave (ULTEM™ 1010 and 9085 resin)	PC-ISO™ ULTEM 1010 resin ABS-M30™	No	No	No	No
PolyJet	Photopolymers	EtO Gamma	MED610 MED620 MED690	Yes	Yes (Connex™ and Stratasys J750™)	Yes	Yes (Stratasys J750)

8.1. FDM

FDM materials offer specialized properties like toughness, electrostatic dissipation, translucence, biocompatibility, UV resistance, V-0 flammability and FST ratings. Slice heights range between 0.127 mm and 0.256 mm, depending on machine and material combination.

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8.1.1. Design considerations (pre-print)

- 8.1.1.1. The surface finish is highly affected by the build orientation. When placing the part for a build, consider the critical surface and orient it along the Z axis for better appearance.
- 8.1.1.2. If possible, minimize the Z height for the fastest building time.
- 8.1.1.3. Consider support removal when orienting the part.
- 8.1.1.4. If dealing with hollow parts, where breakaway support is hard to remove, choose a material/machine combination compatible with soluble support material.



Figure 12: Both options have the same Z height. Orientation 2 will build faster and with less material consumption, and require less post-processing because it does not require support material (shown by the blue lines on Orientation 1).

Table 3: FDM Model And Support Material Compatibility

	Soluble Support				Breakaway Support			
	SR-20	SR-30	SR-110	SR-100	PC Supports	PPSF/PPSU Supports	ULTEM 9085 Supports	ULTEM 1010 Supports
ABSplus		✓						
ABSi	✓							
ABS-M30	✓	✓						
ABS-M30i	✓	✓						
ABS-ESD7		✓						
PC-ABS	✓							
PC				✓	✓			
PC-ISO					✓			
ASA		✓						
Nylon 12			✓					
PPSF/PPSU						✓		
ULTEM 9085							✓	
ULTEM 1010								✓

8.2. PolyJet

8.2.1. Design considerations

PolyJet technology allows the creation of models using either single materials or multiple materials, depending on the 3D printer used. The Vero™ family of materials provides the best approximation for bone and similar hard structures. Tango™ and TangoPlus™ materials are used to replicate soft tissue and vasculature. Digital Materials (the combination of several PolyJet base resins) can be used to approximate materials of intermediate hardness.

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To save on cost, design single-use parts of a surgical model so that they can be inserted into a durable reusable frame. This means you only have to reprint the part that is used each time. An example is the nasal passage model (the consumable model) that's inserted into a rigid model of the head as shown in Figure 13.

Use Meshmixer (meshmixer.com), a free Autodesk software application, for mesh smoothing.

When segmenting data for use with a PolyJet 3D Printer, parts must be exported and reimported as an assembly. In the example below, two separate thresholds are used to create one surface for the skeletal bone and one for the abdominal wall.

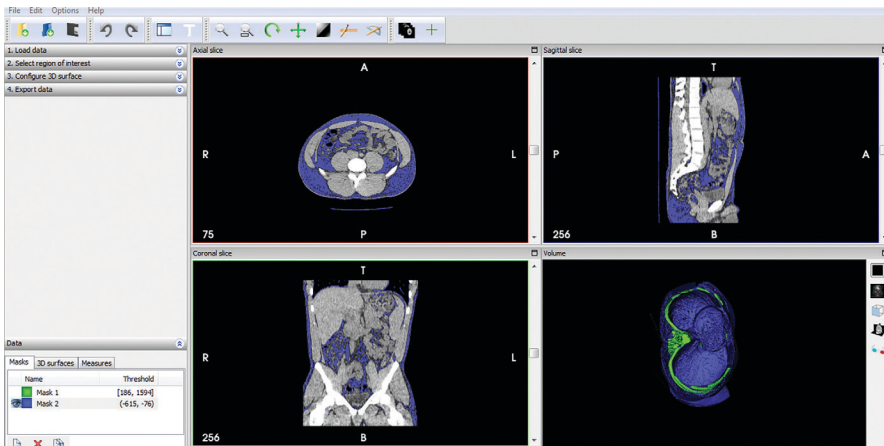
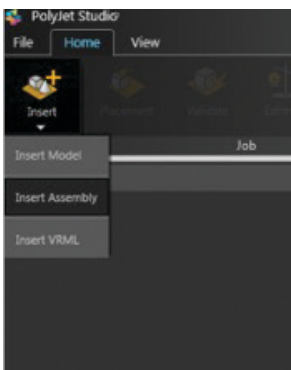


Figure 14: Using double thresholding to create two solid bodies, one for the soft tissue (blue) and one for the bone (green).



Figure 13: Consumable models like the nasal cavity (top) can be placed in a reusable fixture (head model, bottom).

When preparing to print the part, make sure to choose “insert assembly.”



Choose the materials according to the desired properties.

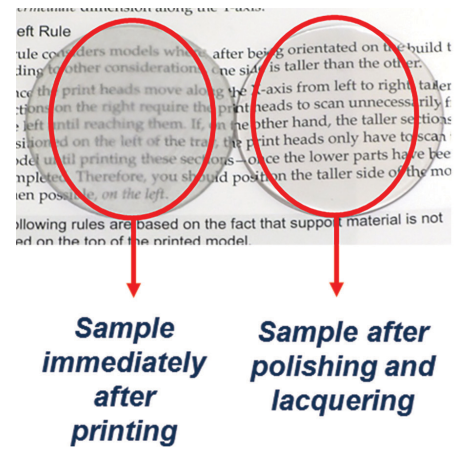
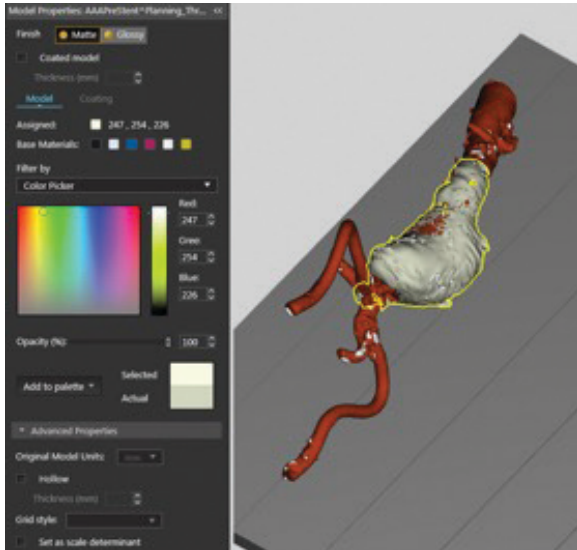


Figure 15: Polishing increases the visual clarity of printed parts.

8.2.2. Making transparent parts

The appearance of VeroClear™ models ranges between transparent and translucent. Post-processing can improve the transparency. To get good, viable results, ensure the surface is as smooth as possible without affecting the clinical realism, prior to printing. The more surface artifacts there are, the worse the transparency will be.

Delicate geometry can be embedded in a clear model to make it more robust. Using excessive amounts of VeroClear can reduce visibility, but polishing helps enhance clarity.



8.2.2.1. Sanding

Sanding enhances the clarity of the model by smoothing the surface and removing imperfections. Several sanding stages may be performed for optimum results:

- Dry sanding: Sand dry surfaces with 200-grit sandpaper. To improve the clarity even further, sand again with 320-grit sandpaper.
- Wet sanding: Use if dry sanding leaves scratches on the model. Use 400-, 600- and 1000-grit wet sandpaper.
- Micromesh sanding: Use 1500-grit and finer sandpaper for a very smooth and polished finish.

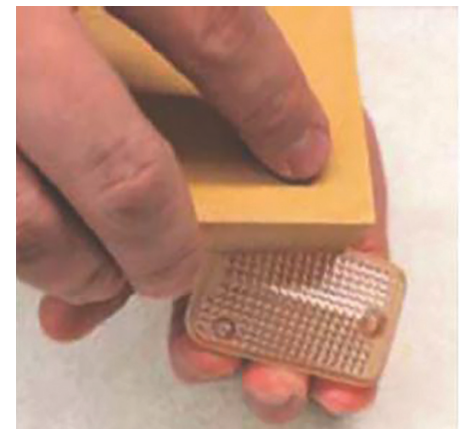


Figure 16: Sanding clear parts for greater clarity.

8.2.2.2. Polishing and Buffing

Apply a polishing compound, such as 3M Plastic Polish, to a buffing wheel or a polishing tool. Work the polishing compound onto all surfaces of the model, then buff off the compound with a soft cloth or clean buffing pad. Finally, spray a thin layer of lacquer to enhance clarity.

8.2.3. Printing vascular structures

PolyJet is popular for 3D printing vascular structures with its Tango (rubber-like) material. To ensure durability and the ability to clear the lumens of support material, follow these recommended parameters when creating the files:

- Internal cavities should be 2 mm or more.
- Wall thickness should be 1.5 mm or greater.
- Models deploying a narrower lumen or thinner walls will be very challenging to clean without damage. If the model is not thick enough, offset the external surface to create the required thickness.
- Add support structures so elements don't float in space and lose shape.
- If available, remove support material from flexible vascular models using a long, thin device with a hollow lumen that can aspirate to clear the channels.
- Build connectors into the model to enable quick connect/disconnect capability with external systems such as intravenous tubing on a flow pump system.
- Be aware when creating models that the intersection of Vero shells and Tango material can create a point of weakness.

8.2.4. Part cleaning

When using SUP706 soluble support in conjunction with flexible TangoPlus parts, it is advisable to allow some space for the support material to expand, since it absorbs water. Use a sharp elongated tool (screwdriver, toothpick or metal wire) to debulk the material before soaking it in NaOH (sodium hydroxide) solution.

Use the "Lite Grid" support option to allow easier support removal.

Use an iterative process of washing with low pressure water, removing free support material to assure cleaning of support from flexible vessels. Using a high-pressure water jet may rupture the vascular wall.

Do not soak the models for more than a few hours at a time, as support material tends to absorb water and swell. If facing a complicated geometry, remove some of the support to allow a place for expansion.

Avoid sharp corners, where possible. Use local smoothing to create smooth transitions around corners



Figure 17: The effect of polishing on transparent and translucent parts.

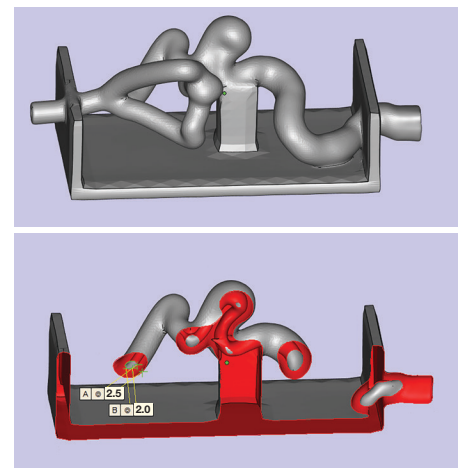


Figure 18: Recommended parameters for internal cavity and wall thickness.

9. Example A: Automatic Aortic Root Segmentation Using Vitrea Advanced Visualization

(The following information is developed from “Vitrea Advanced Visualization: 3D Print Workflow,” copyright and courtesy of Vital Images, Inc.).

9.1. Load one or several 3D datasets in the Vitrea software.

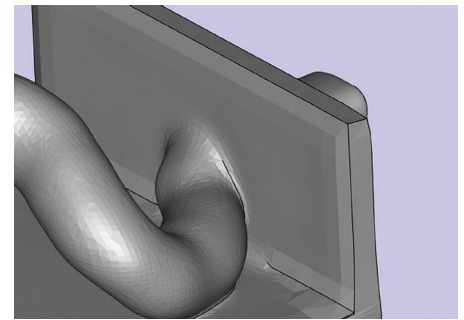
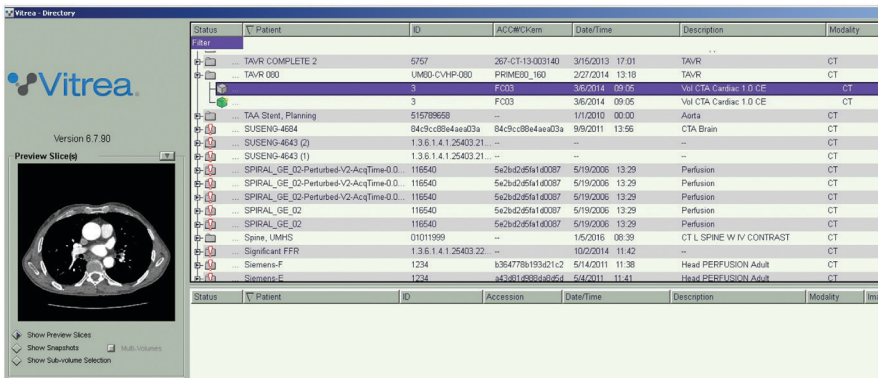
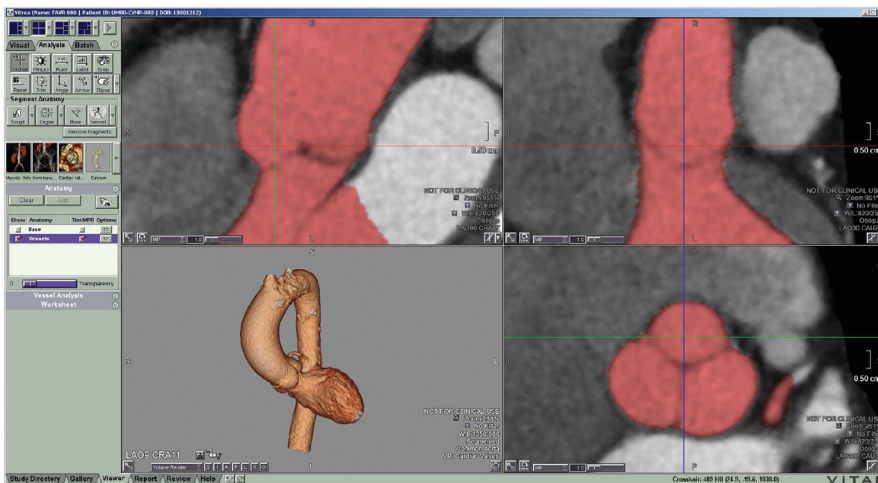


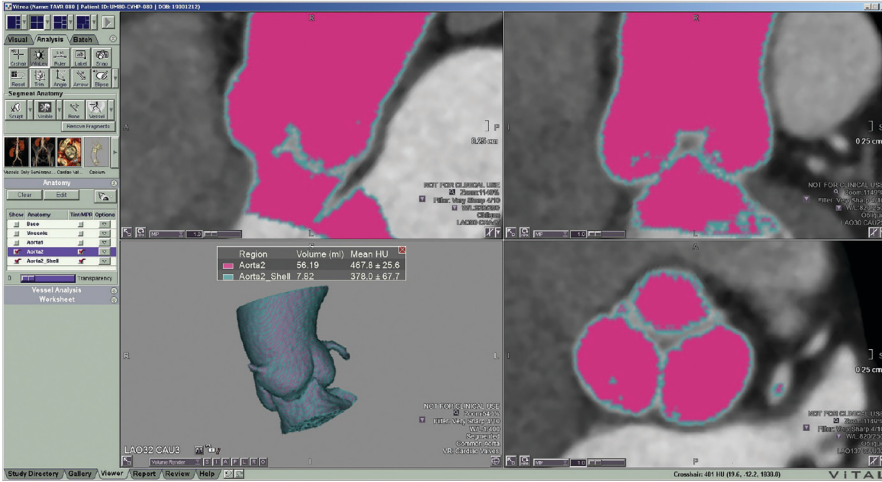
Figure 19: Smooth transitions (fillets) will be more durable than sharp corners.

9.2. Auto-segmentation starts after selecting a clinically oriented protocol.

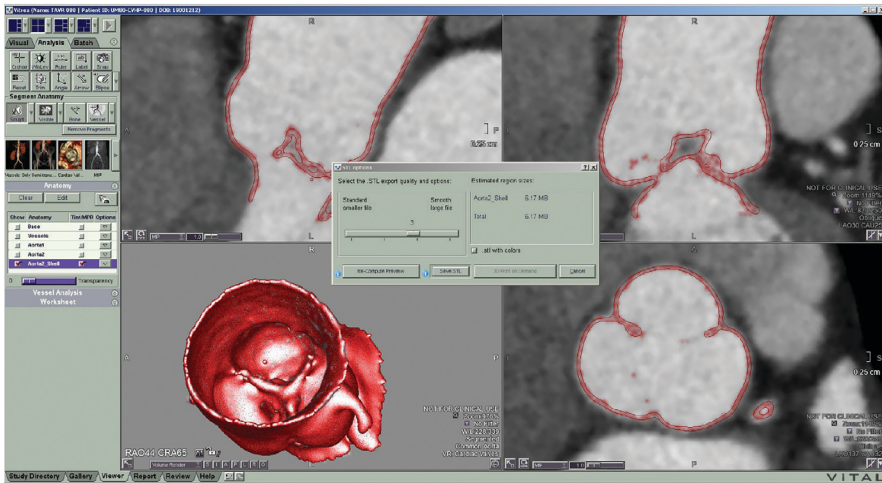


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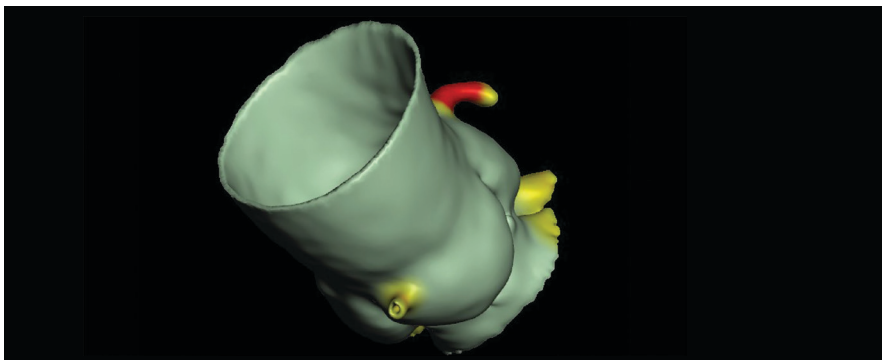
9.3. Refine the auto-segmented parts using interactive segmentation tools.



9.4. After verification using the STL preview, save the DICOM data as an STL file for 3D printing.



9.5. The STL files can now be loaded, modified and used for 3D printing.

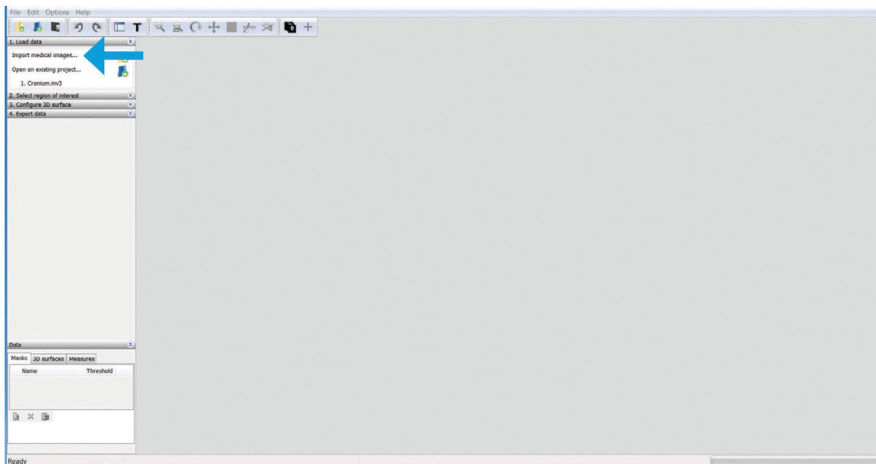


10. Example B: Bone Segmentation Using InVesalius Software

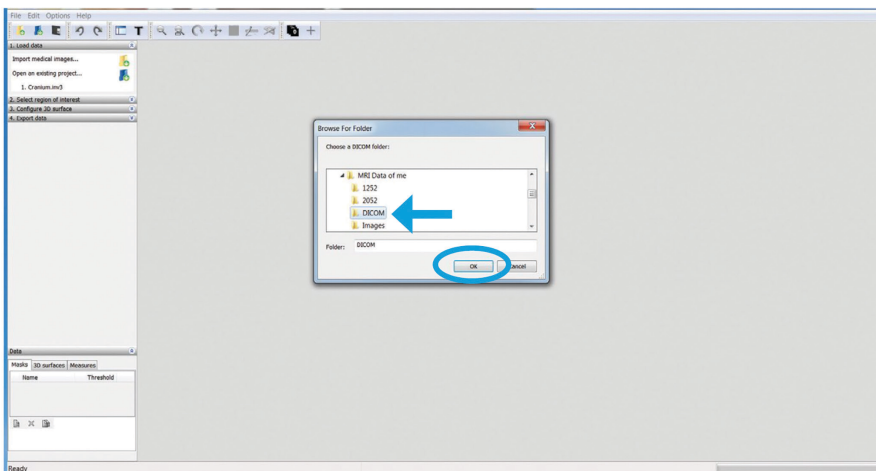
10.1. Obtain the DICOM data.

10.2. Convert the DICOM data into an STL file.

10.2.1. Open InVesalius and click on **Import Medical Images**.

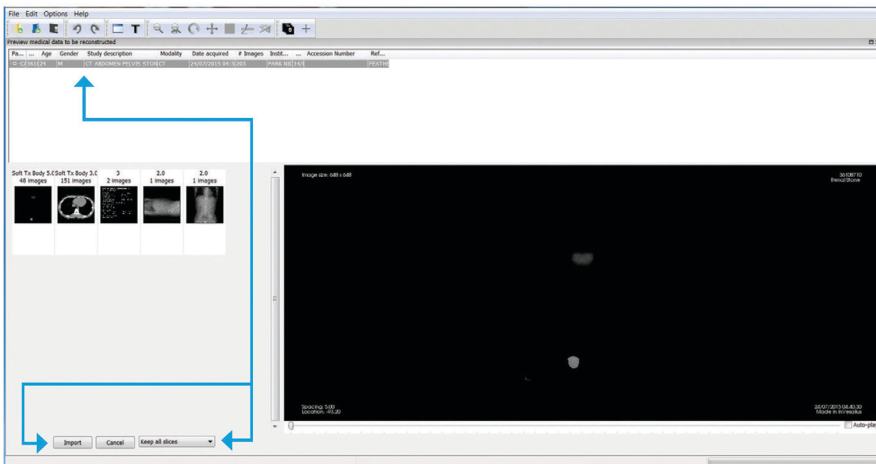


10.2.2. Select the DICOM folder that contains all the images from the scan and press **OK**. InVesalius will begin to upload the files.

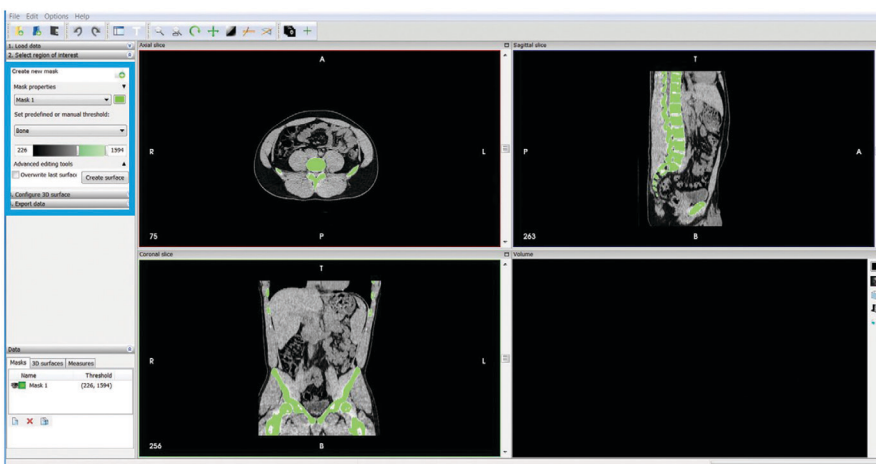


DATA SEGMENTATION FOR MEDICAL 3D PRINTING

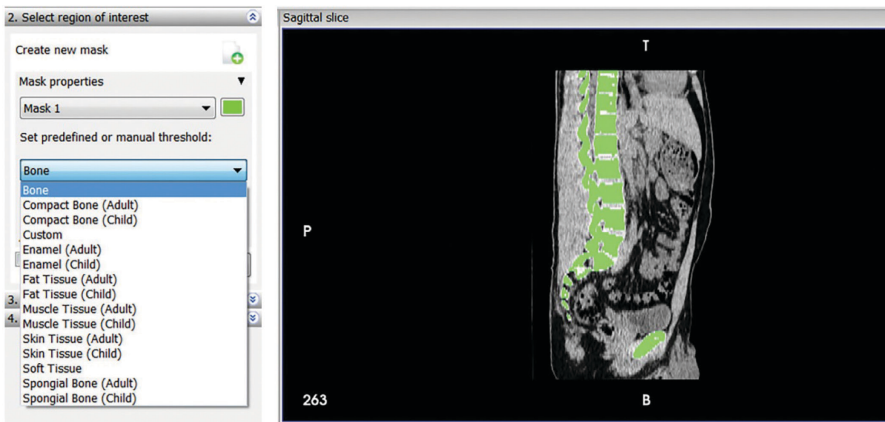
10.2.3. Once the files have been uploaded, make sure the patient files are highlighted and press **Import**. The software will begin generating multiplanar visualization. You can choose to keep all slices or skip some slices to help control file size. This example shows **Keep all slices** for this file.



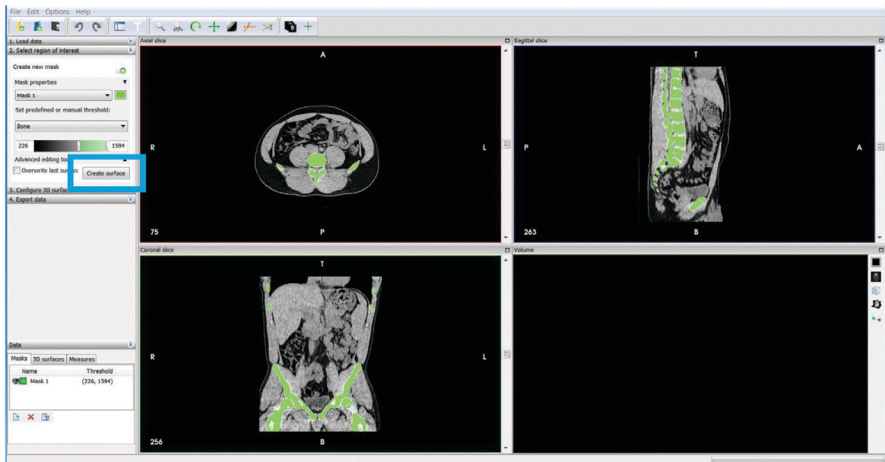
10.2.4. Next, create a new mask. A mask is a representation of a certain density within the images, derived from the different shades of gray. You can customize the mask by moving the threshold bars. Or you can choose a predefined mask. In this example, **Bone** is chosen (see the second image below). You can scroll through the different slices by clicking on one of the three slice boxes (axial, sagittal or coronal) and using the scroll wheel on your mouse.



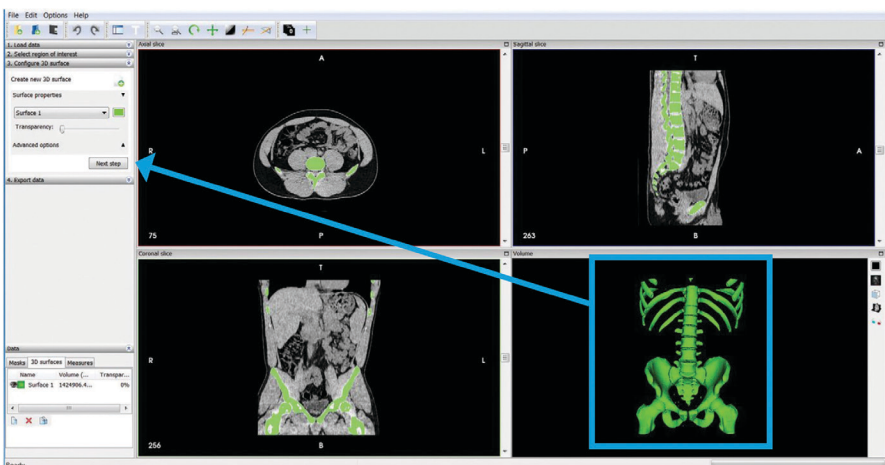
DATA SEGMENTATION FOR MEDICAL 3D PRINTING



10.2.5. When you are satisfied with your mask, press **Create surface**.

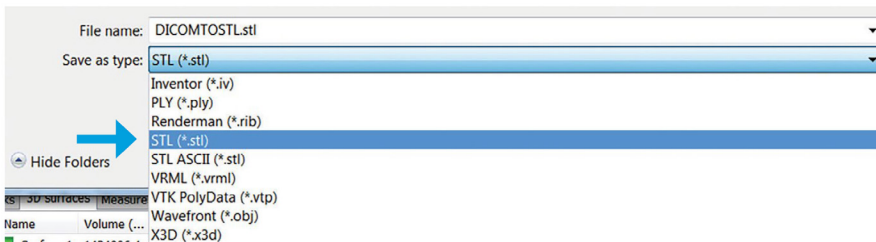
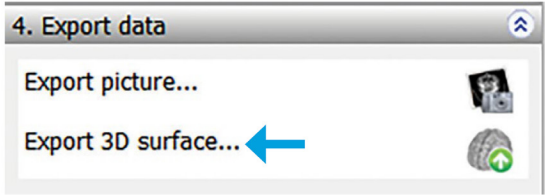


10.2.6. This will generate a surface file that can be saved as an STL file. You can modify the transparency if desired, then press **Next step**.



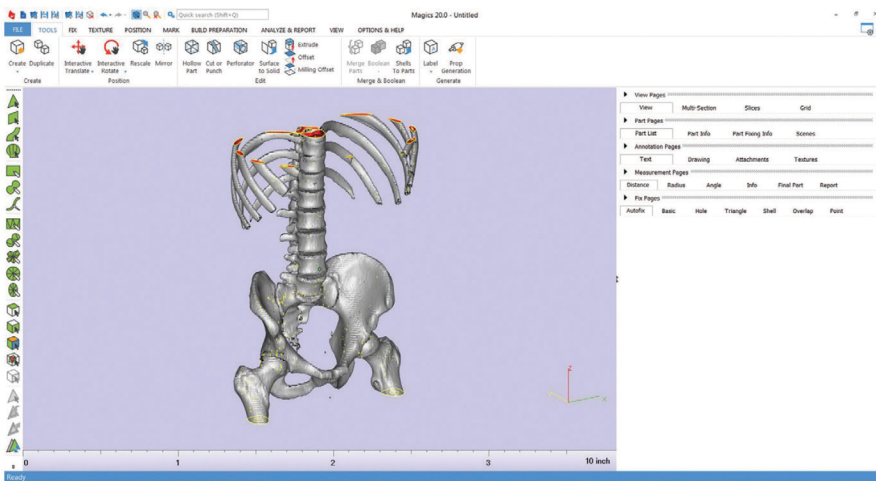
DATA SEGMENTATION FOR MEDICAL 3D PRINTING

10.2.7. The file is now ready to be exported. Click Export 3D surface.



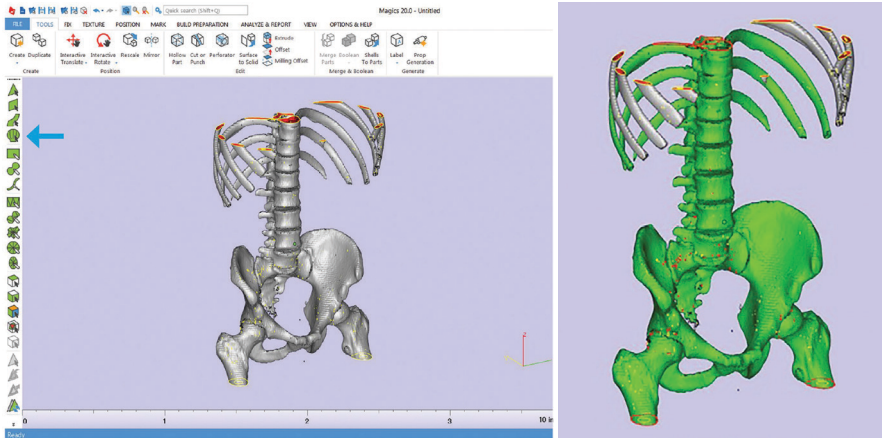
10.3. Fix the file with STL Editing Software

10.3.1. Now that you have the STL file you can bring it into the STL editing software to prepare it for 3D printing. Be sure to convert the surface file into a solid model and remove any noise shells so it will print well. This example uses Materialise Magics software.

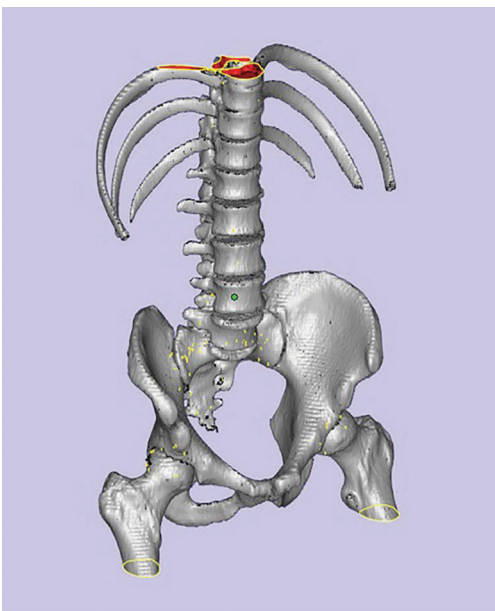


DATA SEGMENTATION FOR MEDICAL 3D PRINTING

10.3.2. First, remove the noise shells. To do this, select the main shell, then select **Inverse marked** to automatically select the unwanted shells. Then delete those shells by pressing **Delete** on the keyboard. This will delete any surfaces not attached to the main file. In this example, the green highlighted section is the file selected to be 3D printed.

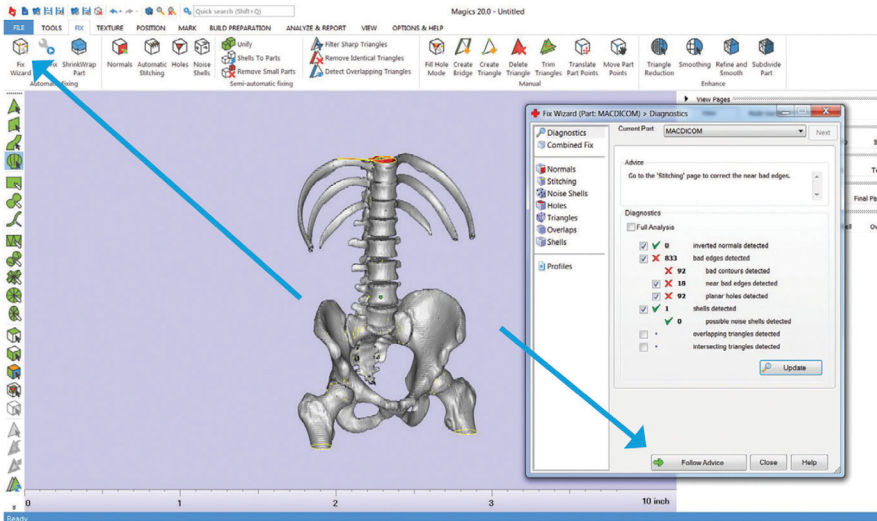


10.3.3. With noise shells deleted, the file will look like this:

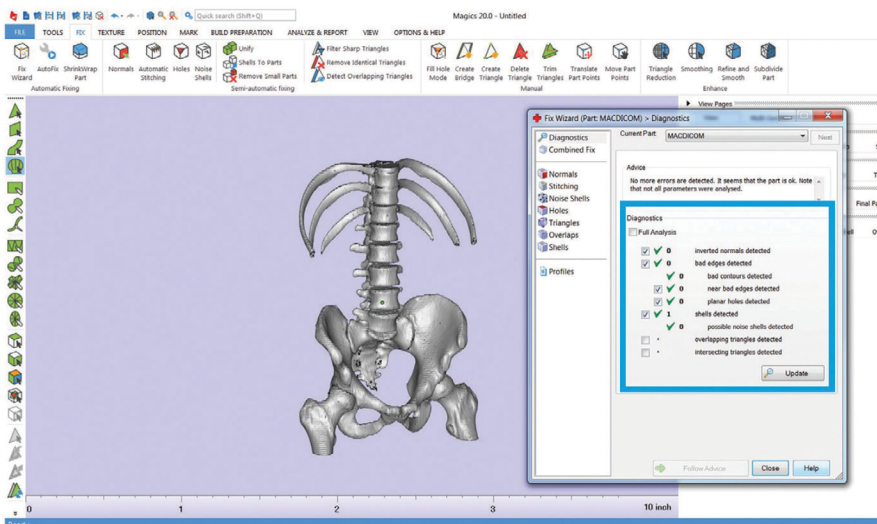


DATA SEGMENTATION FOR MEDICAL 3D PRINTING

10.3.4. The file is still just a shell so bring it into the Fix Wizard and run automatic fixes by clicking **Follow Advice** on the part until it is a solid body without any overlapping surfaces. This will require about six automatic fixes.



10.3.5. After the software has fixed all the problems, there should be only green check boxes in our diagnostics tab (see below). Save the fixed STL file and it is ready to 3D print.



10.3.6. The STL file is now fixed and can be printed with any 3D printer.



CONTACT

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