How to 3D Print Anatomical Models for Preoperative Planning and Enhanced Patient Consent

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Introduction

3D printed models are becoming increasingly useful tools in today's practice of personalized, precision medicine. As cases become more complex and treatments truly unique, visual and tactile anatomical models can enhance understanding and communication in the process of reaching a patient-specific solution.

Healthcare professionals, institutions, and organizations across the globe are using 3D printed anatomical models as reference tools for preoperative planning, intraoperative visualization, and sizing or pre-fitting medical equipment for both routine and highly complex procedures that have been documented in hundreds of publications.[1] Physicians often save time preparing for and conducting surgeries, leading to drastically reduced operating room costs while lowering patient risk, anxiety, and recovery time.

This guide offers a practical, step-by-step walkthrough for physicians and technologists to go from patient scan to 3D printed model, reviewing best practices for setting up a CT/MRI scan, segmenting datasets, and converting files to a 3D-printable format.

> *"A unique advantage of image-based 3D printing is the ability to demonstrate anatomic spatial relationships with submillimeter accuracy."*

Jeffrey D. Hirsch, MD
Assistant Professor, Director of Community Radiology, Department of Diagnostic Radiology
University of Maryland School of Medicine

Anatomical models printed on Formlabs machines are already being used across several sub-specialties of surgery, including but not limited to orthopedic, cardiothoracic, vascular, oral and maxillofacial (OMFS), oncology, plastics, reconstructive, urology, and pediatric. This tutorial provides an overview of steps that can be applied to any Digital Imaging and Communications in Medicine (DICOM) dataset, which is the standard format for image storage in any modern picture archiving and communication system (PACS).

WHAT YOU'LL NEED FOR ON-SITE 3D PRINTING

CT or MRI scan and associated DICOM file
  • Recommended slice thickness: 0.25 mm-1.25 mm[2]

Computer with medical imaging software for segmentation, or use of an outsourced segmentation service

Form 2 3D printer and resin, for example:
  • White Resin for orthopedics or OMFS
  • Clear Resin for cardiovascular or urology
  • Dental SG Resin for surgical guides (approved uses only)

Form Wash and Form Cure for post-processing 3D prints (recommended for medical models)

Applications and Benefits of 3D Printed Anatomical Models

> Formlabs is an industry-leading provider of 3D printers and materials used by healthcare providers to support the practice of medicine. Please consider your intended use, local regulations, medical imaging software clearances, material data sheets, biocompatibility requirements, protected health information, and institutional standards before 3D printing or using anatomical models.

Depending on your institution, anatomical models may be used for patient- or pathology-specific purposes:

- Preoperative planning and intraoperative reference models for surgeons
- Device sizing (e.g., mandibular plates) and surgical tool design*
- Molds for implantable material or prostheses*
- Trainee education and simulation labs
- Patient education and enhanced informed consent

*May be subject to regulation and/or require institutional approval

Numerous published case studies and ongoing efforts have demonstrated the potential of 3D printing in a clinical setting. Published use cases include preoperative planning[3], intraoperative use[4], patient-specific instrument guides[5], custom-tailored implants[6], molds for bone cement[7] or polymethyl methacrylate (PMMA) implants[8], prostheses[9], and trays.

These use cases have seen success in a variety of fields and surgical specialties, including orthopedic, cardiac, oral and maxillofacial (OMFS), vascular, neurological, cardiothoracic, musculoskeletal, plastics and non-facial reconstructive surgery, oncology, pediatrics, interventional radiology, and others.

> *"As much as I'd like to think that my brain can reconstruct a 3D interpretation from a 2-D CT scan, I was surprised by the relative inaccuracy of the approach that I've been using for 20 years. The 3D printed models have been invaluable in planning, particularly when using the daVinci robot."*
>
> **Dr. Ronald Hrebinko**
> Urologist and Associate Professor of Urology
> University of Pittsburgh School of Medicine

3D printed models can also have substantial benefit for educating medical residents, fellows, and students[10]. Patient-specific models are especially appealing when considered against the cost of cadaveric specimens and animal testing and their associated requirements for laboratory space, surgical instruments, and disposal.

Top 5 Medical Disciplines Leveraging 3D Printing Technology
PUBLICATIONS ON PLANNING, EDUCATION, AND VISUALIZATION

| | Cardiac | Orthopedic | Vascular | Neurosurgical | Hepatobiliary |
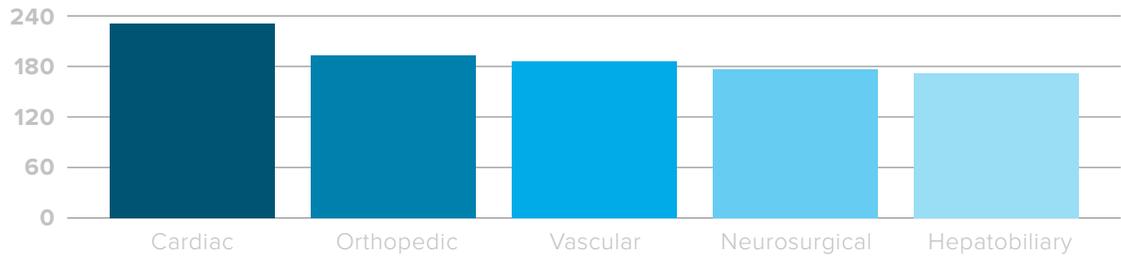
Chepelev et al, 3D printing in Medicine, 2017.
Image retrieved from http://www.materialise.com/en/blog/3d-printing-us-hospitals

Explore our collection of research publications *to learn more about how Formlabs printers and materials have been used in healthcare.*

Widespread use of advanced visualization in radiology has been key for diagnosis and communication among physicians. While these visualizations have traditionally lived in 2D planes from CT or MRI scans as DICOM files, software developers have recently created tools to reconstruct diagnostic images as 3D anatomic renderings.

3D printed models are a natural progression from these various 3D visualization options, and offer many additional benefits, such as tactile feedback and other tangible information, that visualizations cannot.

When a patient's severe foot deformity could not be fully conceptualized with 2D images, surgeons used a 3D printed model to plan how to correct gait with equipment prior to surgery and communicate with clinical staff and registrars.

For example, examining a custom 3D printed model led an orthopedic surgeon in the UK to find a lower risk solution to a young boy's abnormal forearm injury.

"Access to the model changed the standard treatment indicated by the CT scans from a four-hour complex osteotomy to a simple, much less invasive 30-minute soft tissue procedure," said Dr. Michael Eames.

The successful surgery was completed in just under 30 minutes—a decrease of over three hours from the originally planned time in the operating room, saving the hospital an estimated $5,500. Subsequently, the patient spent less time in postoperative care and recovered faster[11].

From Patient Scan to 3D Model

IMAGING

MRI — CT

SEGMENTATION

DICOM Image
Convert + Segment

DESIGN

3D Model
Generate with CAD Software

PRODUCTION

3D Print
Manufacture Model

POST-PROCESSING

Final Part
Clean + Polish

APPLICATION

Ready to Use

Workflows from Scan to 3D Printed Model
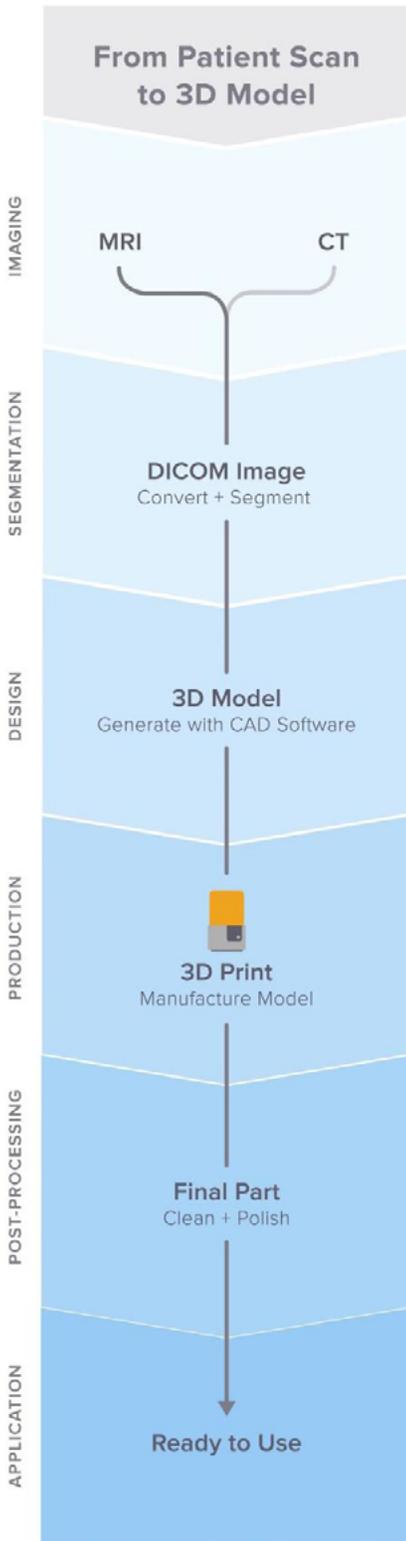
Generating 3D printable files and 3D printed models requires specific considerations and minor modifications in the medical imaging workflow.

The adapted workflow can be summarized in three stages: image acquisition, image segmentation, and 3D printing.

IMAGE ACQUISITION

Image acquisition is the first step that is already integrated into the workflow. The most common imaging methods useful for 3D printing are CT and MRI. In general, 3D models can be printed from any volumetric image dataset (slices) with sufficient contrast to differentiate tissues. Cone Beam CT is also commonly used for dental and ENT imaging, but the contrast resolution may be poorer than with traditional CT, making segmentation more difficult[12]. Find guidelines for setting up patient scans for 3D models in the second portion of this white paper.

IMAGE SEGMENTATION

The main objective of this step is to reduce the complexity of the original image, leaving the characteristics of interest intact and isolated. After a radiologist acquires the DICOM, they must obtain the regions of interest (ROI) to be rendered as a 3D printable object. The process of identifying and separating tissues and other regions of interest is called segmentation. Depending on the complexity of the model, this is either performed by a radiology technologist under the direction of the radiologist or by the radiologist directly. When the segmentation is done, it is reviewed with the surgeon for final approval[13].

A range of commercial and open-source software is available (see the list at the end of this section) for the segmentation process. Consider the intended use, regulatory requirements in your geographic location, and guidelines within your institution before selecting a software solution.

Steps in ROI segmentation can involve automatic methods (e.g., thresholding, edge detection, and region growing) or manual selection and adjustments. Thresholding uses parameters that are identifiable and attributable to the specific ROI, such as bones with higher Hounsfield units relative to their surroundings.
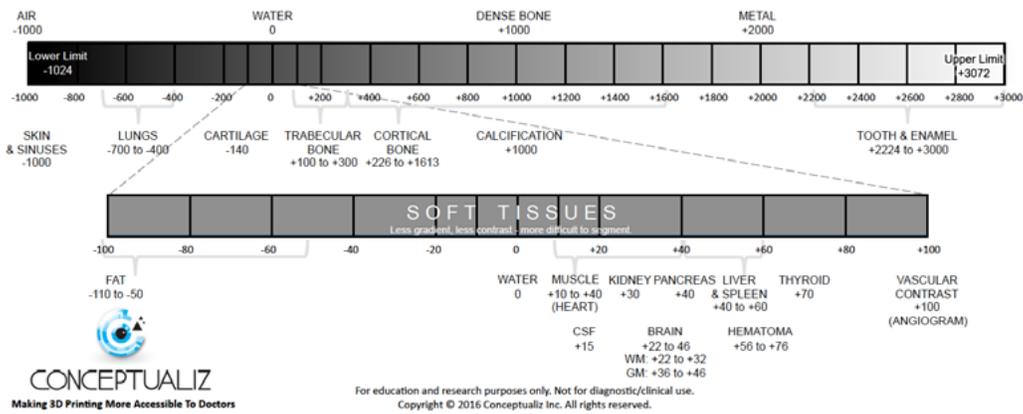
Thresholds may need to be dynamic and involve more complex algorithms to account for factors such as CT noise and beam hardening that may produce artifacts and other undesired results. Another option is to use region growing to automate segmentation, where an algorithm assigns voxels as belonging to one part or another based on similarity or deviation from its surrounding voxels. Additional adjustments and refinements may be necessary.

After segmentation is finished, convert segmented objects into a file type that a 3D printer can use. This file type is typically an STL or OBJ file format.

After the conversion, perform any necessary physical adjustments that are more common in 3D modeling, such as smoothing out surfaces, filling holes, and fixing other minor features. These adjustments can be performed by a technician on a variety of CAD or CAM software and should always include physician review to ensure that the output is clinically useful.
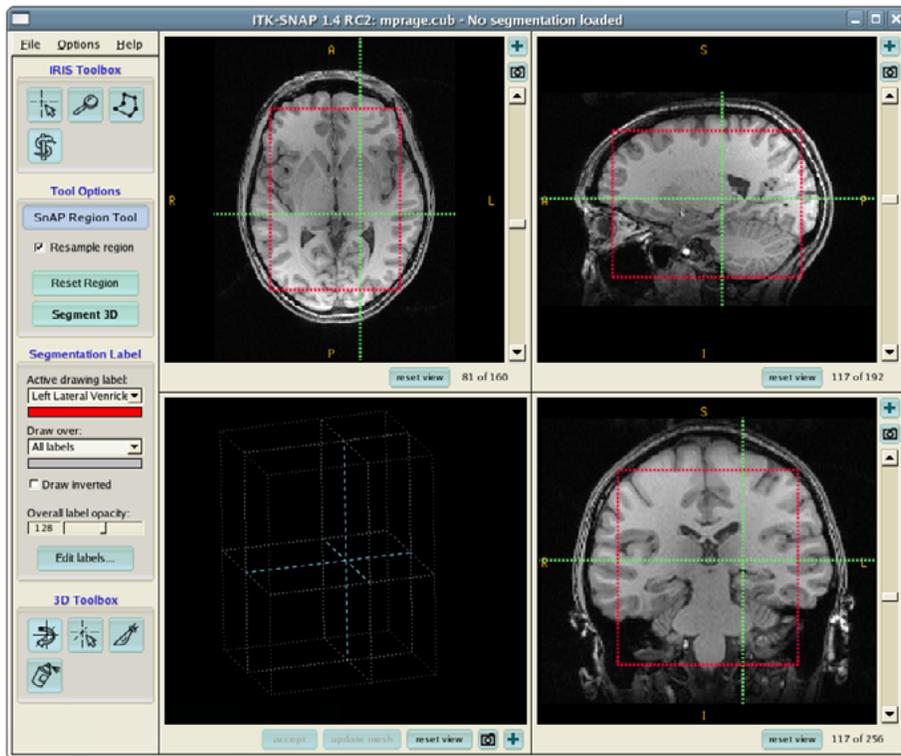
After a radiologist acquires the DICOM, they must obtain the regions of interest (ROI) to be rendered as a 3D printable object.
Source: ITK-Snap
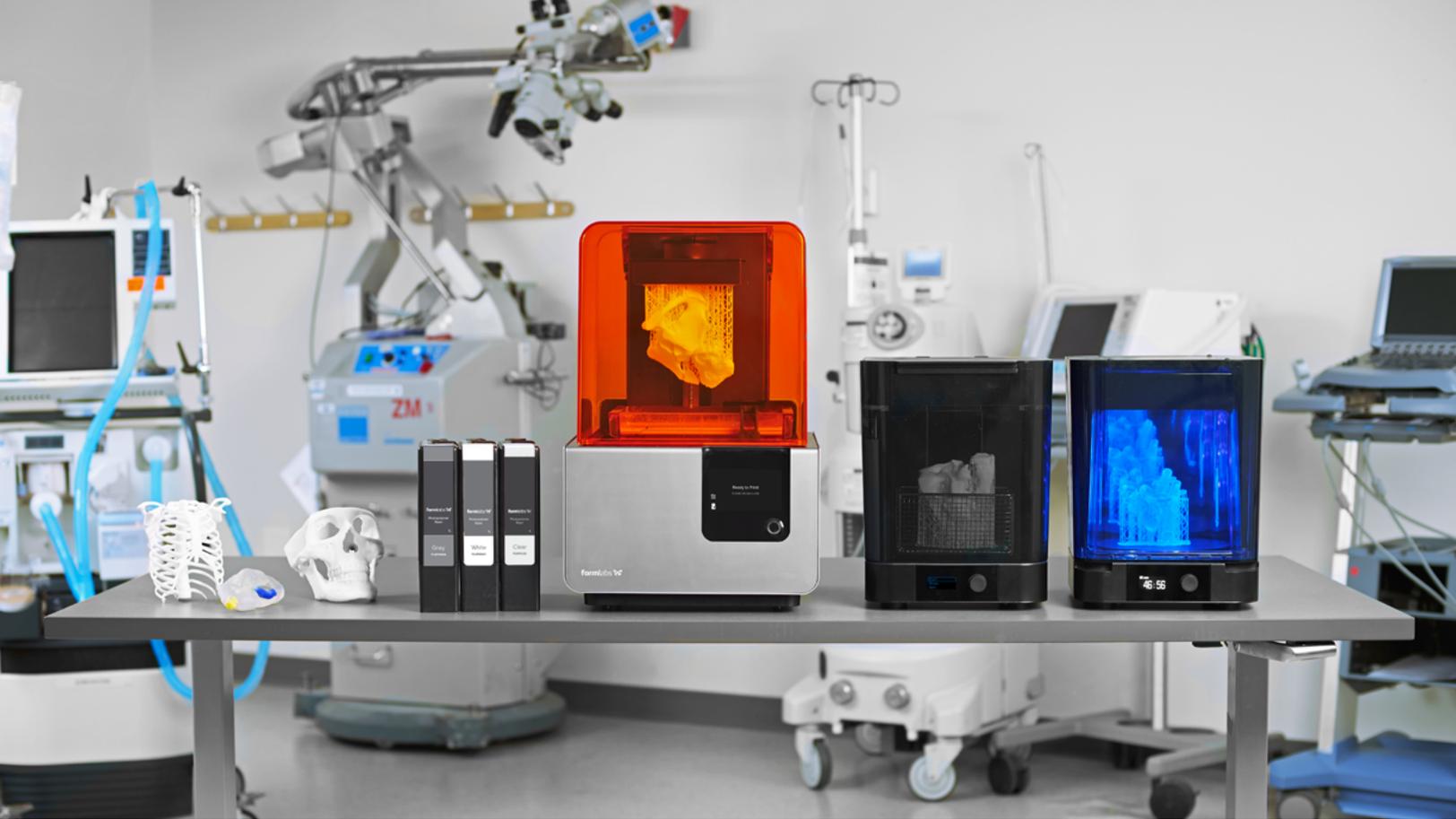
In-house 3D printing enables healthcare providers to quickly create high-resolution medical models.

3D PRINTING

Once the final file is ready, it can be exported and sent to a 3D printer for fabrication. There are several key factors to consider when choosing the right 3D printing technology, including: the cost of the printer, software, and materials; print speed, accuracy, and resolution; ease of use and access to customer service; and the type of printing materials, including biocompatibility and the ability to be sterilized for certain use cases.

After printing, parts must be washed in isopropyl alcohol (IPA) to remove excess resin and, depending on the material and applications, post-cured in a cure chamber. All biocompatible resins require post-curing before use, and Formlabs Standard Resins, such as White and Clear Resin, increase in strength and stability after post-curing.

Additional information on printability
Visit our **software support** and **resources pages** for additional information on how to set up files for printability and to learn more about design specifications, such as internal supports and **minimal wall thickness**.

POTENTIAL SOFTWARE AND HARDWARE OPTIONS FOR ON-SITE 3D PRINTING

Note: only one software is required per section, which represent steps in the workflow. This list is meant to facilitate reference and research only and is not an endorsement of any particular software or vendor. For those who want anatomical models without segmentation or printing on-site, specialized service providers offer conversion, segmentation, and/or printing services for a fee (e.g., **Anatomage**, **Armor Bionics**, **Axial3D**, and **Materialise**).

Please consider your local regulatory guidelines and intended uses before selecting a software solution.

Conversion + Segmentation	
Materialise Mimics*	ITK-SNAP
3D Slicer[14]	4DICOM
Axial3D	Seg3D
Osirix	Embodi3D (DICOM to STL conversion, no segmentation)
Ossa 3D	Vitrea Vital Images
Anatomage Medical Design Studio	

Editing Preparation + File Manipulation, Smoothing, and Identification		
Blender	Materialise 3matic	Autodesk Meshmixer

Support Generation + Print Orientation	
Formlabs PreForm	Materialise e-Stage Note: In cardiac cases, advanced support removal from within valves may be necessary (**PreForm video tutorial**)

Printer	
Formlabs Form 2 or Form Cell system	Formlabs Fuse 1

Print Post-Processing	
Formlabs Finishing Kit	Form Wash and Form Cure
Ultrasonic Cleaner (e.g., GT Sonic)	CUREBox CB-4051

* Formlabs and Materialise have partnered to offer an end-to-end bundle in the US, Europe, and Japan. Mimics inPrint is a dedicated software solution to create accurate virtual anatomical models based on medical images and to prepare files for 3D printing. Integrated into clinical environments (PACS), Mimics inPrint includes pre-defined workflows with a direct link to Formlabs 3D printers.

Setting Up Patient Scans for 3D Models

Some conventional medical imaging scans cannot be converted into high-quality 3D models to produce clear, accurate anatomic structures of interest. Plain radiographs (X-rays) and ultrasounds are not commonly used for 3D printing, and these imaging modalities are not recommended.

The most commonly obtained imaging modalities for evaluation of internal structures are CT scans and MRI imaging. These scans generate a DICOM file. DICOM is the standard for storing and transmitting medical images and can be considered a series of slices.

DICOM images cannot be edited in 3D design software or sent directly to a printer. In order to convert a DICOM file into a format suitable for 3D printing, such as an STL or OBJ file, a separate software is required to calculate the surface area of the structure of interest. This surface will then become the 3D model.

Almost any DICOM file with sufficiently fine detail (e.g., thin slices) can be converted into a format that allows for 3D printing of the structure(s) of interest.

> **The articles below may be helpful when preparing, printing, and post-processing anatomical models:**
>
> **Design Models for Printability**   **Post-Curing Prints**
>
> **Design Specs and Best Practices for Geometric Features**   **Post-Processing Basics**
>
> **Cleaning Internal Cavities and Channels**

Criteria for Generating a Printable Scan

The first consideration when turning a CT or MRI scan into a 3D model is what needs to be shown; bones, vessels, and solid organs all need to be modeled in different ways. A model with obsolete structures not only distracts from the focus of the model, but will also be more difficult to manufacture. A scan with proper characteristics makes it easier to create a 3D printable model. Basic features to consider are **intravenous contrast** and **slice thickness.**

For 3D models of bone structures, noncontrast images will likely be sufficient for accurate, detailed printing. Contrast-enhanced scans are almost always required for models that include solid organs, tumors, or vascular structures.

Introductory Information about Contrast

The variation in brightness on a CT scan allows segmentation software to separate out different structures, which allows you to print the area or organ of interest. Some structures, such as bones, are inherently bright on CT scans. This makes them easy to 3D print when starting from a noncontrast CT. However, intravenous (IV) contrast is necessary when you want to 3D print a blood vessel, tumor, or most organs. The contrast is given to the patient just prior to obtaining the scan, and will enhance these structures. With IV contrast, blood vessels (arteries and veins) and solid organs (e.g., the liver, kidneys, spleen, heart, and brain) are brighter on the scan, which allows segmentation software to accurately separate them from the surrounding tissues. See the images below for comparison of noncontrast and contrast-enhanced CTs of the abdomen.
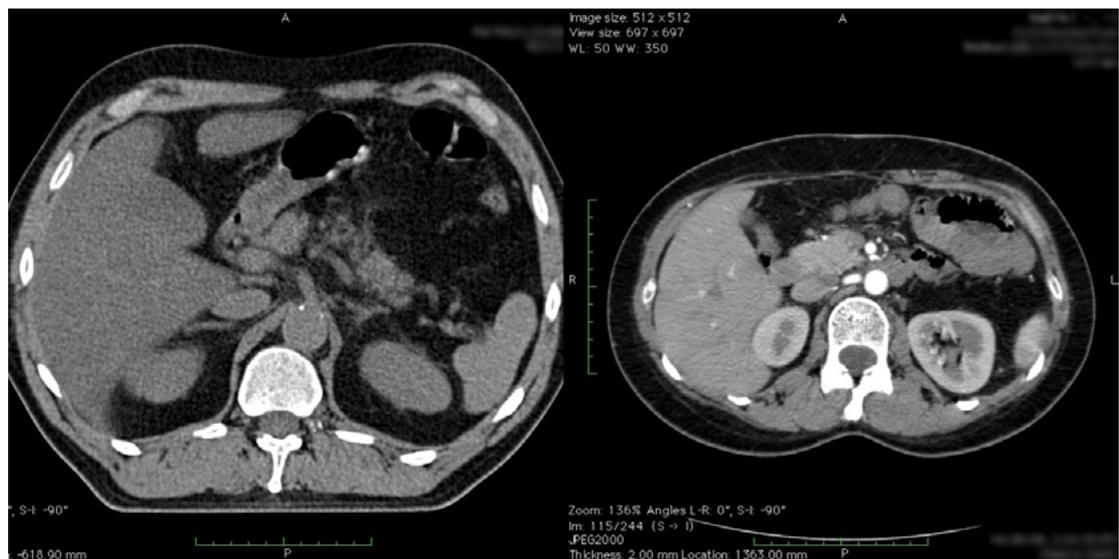
The effect of intravenous contrast is shown with these two axial (transverse) images of CT scans of the upper abdomen. In the righthand scan the aorta is enhanced, whereas on the lefthand scan the aorta appears quite similar to the adjacent soft tissues. Contrast allows for isolation of desired structures in post-processing. Source: Embodi 3D

In addition to contrast enhancement, slice thickness and resolution are equally important to consider when planning for 3D model creation. Most clinically useful scans are obtained with adequate resolution for 3D printing. However, if you try to 3D print an anatomical model from a scan with thick slices, your model will have a rough finish. According to numerous sources, it is very important to use scans with slices less than **thinner than 1.25 mm** when creating a model for 3D printing.
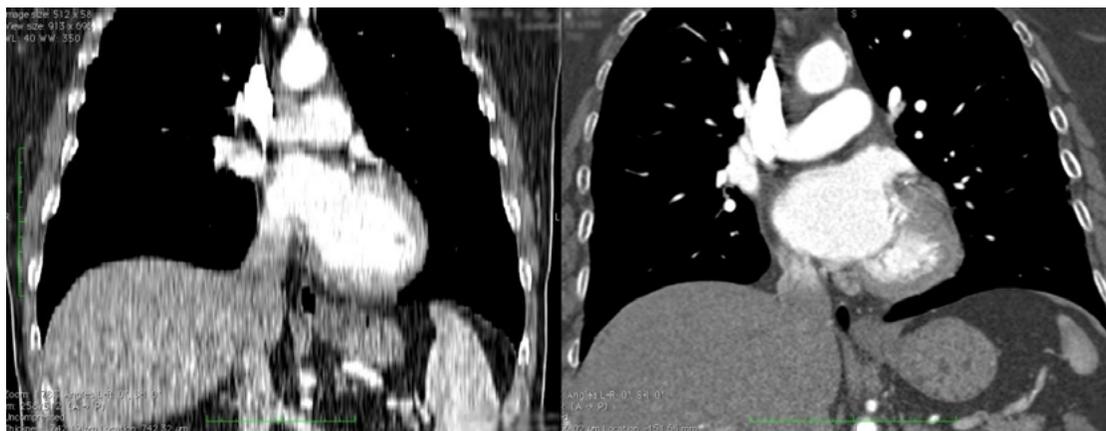
Two CT scans of the chest. The image on the left shows a coronal view built from slices that are 5 mm thick, whereas the righthand scan demonstrates a similar view of the chest using slices that are only 1 mm thick. The thick slices in the lefthand image generate coarse structures that will lead to a lower quality printed model. Source: Embodi 3D

The thickness of slices captured by a CT or MRI scan translates directly into the detail generated in a 3D scan. Depending on the item of focus, image sections should be reconstructed with isotropic voxels of 1.25 mm or less[15]. According to a presentation by the Mayo Clinic in March 2016, slices as thick as 1.5–3 mm may be used for larger structures, whereas 0.75 mm may be used for fine bone[16]. Thicker sections may compromise model accuracy, while very thin sections (e.g., <0.25 mm) could require extensive segmentation and STL refinement, particularly in the presence of image artifact. Cardiac models demonstrate sufficient accuracy with 0.5 mm sections, but thin objects such as the orbital floor may require thinner sections[17]. Generally, thicker sections may produce unclear or less accurate printed models. Nevertheless, unnecessarily thin sections may create significantly more work in the post-processing phase.

Regulatory Considerations

Please consider local regulations, material data sheets, patient information, and institutional requirements before 3D printing or using anatomical models. For physicians in the US, refer to the **latest FDA presentation summarizing its guidance document**[18]. Please note that these documents and guidelines are subject and likely to change. Always confirm you comply with the latest recommendations.

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Conclusion

Barriers to entry for personalized, precision medicine are rapidly lowering. The advent of affordable professional-grade desktop 3D printers has enabled healthcare providers to produce patient-specific anatomical models for a variety of specialities with inspiring results. In some cases, the initial cost of high-quality a printer was covered by the costs associated with time saved in the OR room after a surgeon used a 3D printed model to prepare for a single complex procedure[19].

"Medicine is not one size fits all, and when a tool like desktop 3D printing comes along that allows you to create personalized medical solutions, it is a no brainer to utilize it to its fullest capacity."

Todd Goldstein PhD
Instructor, Feinstein Institute for Medical Research
Director, 3D Printing Lab, Northwell Ventures, Northwell Health

Understanding the workflows required to integrate 3D printing is key to a successful operation. This tutorial addressed what you need to get started, popular workflows and tools, and techniques to facilitate the progression from patient scan to 3D printable model.

Contact us to learn more about introducing 3D printing into your institution and join the community of innovators in precision medicine.

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