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Three-Dimensional Printing of a Complex Aortic Anomaly

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TITLE:

Three-Dimensional Printing of a Complex Aortic Anomaly

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KEYWORDS:

Three-Dimensional Printing, Cardiac Surgery, Congenital Aortic Diseases, Aortic Anomaly, Preoperative Planning, Intraoperative Guidance

SHORT ABSTRACT:

Here, we present a protocol to use three dimensional printed models for pre-operative planning and intra-operative reorganization of complicated vascular locations when handling a congenital aortic anomaly.

LONG ABSTRACT:

Complex congenital aortic anomalies include diverse types of malformations that may be clinically asymptomatic or present with respiratory or esophageal symptoms. These anomalies may be associated with other congenital heart diseases. It is hard to identify the accurate anatomic vessel location from two-dimensional imaging data, such as computed tomography. As an additive manufacturing method, three-dimensional (3-D) printing can covert the acquired imaging data into 3-D physical models. This protocol describes the procedure for modeling the volumetric DICOM imaging into 3-D data and printing it as an anatomically realistic 3-D model. Using this model, surgeons can identify the vessel location of complex aortic anomalies, which is helpful for pre-operative planning and intra-operative guidance.

INTRODUCTION:

Congenital aortic anomalies are extremely rare congenital malformations of the aortic arch system. They can be diagnosed either by imaging analysis or by evaluation of entities like dysphagia or subclavian steal[1]. In clinical scenarios, it is important to identify the anatomical anomaly in the confined surgical space that has limited visualization during the surgery[2,3]. Currently, conventional planar two-dimensional (2-D) imaging, such as computed tomography (CT) and magnetic resonance imaging (MRI), are usually presented to surgeons before the surgery. However, it is difficult for surgeons to image the anomaly based on the 2-D imaging. Consequently, they could encounter unpredictable difficulties while trying to separate the complex aortic vessels during surgery. Unpredictable injury to the vessel, the trachea and the esophagus could occur and result in disastrous outcomes.

In the last decade, 3-D imaging modeling has been used in cardiac surgery to help surgeons understand the complex anatomic anomaly[4-7]. Three-dimensional (3-D) printing technology can help convert the modeling data into a physical model. Compared with the digital reconstruction, 3-D printed physical models could present a better understanding of the anatomical details and provide an intuitional view of the malformation. For aortic anomaly surgery, the printed intuitional 3-D model is significant because poor understanding of aortic locations could be disastrous to patients. During the surgery, any mistake could lead to unpredictable bleeding and injury. Using the printed models, surgeons can fully understand the spatial relationships of aortic branches. During the surgery, the surgeons can also perform real-time review of the 3-D models to avoid confusion of the complex vascular locations.

Here, we present a protocol to apply 3-D printed models for pre-operative planning and intra-operative guidance while dealing with congenital aortic diseases. Kommerell's diverticulum, a type of complex congenital aortic anomaly, was selected as a case study. The steps include diagnosis based on computed tomography angiography (CTA) imaging, partitioning regions of interest, building 3-D models, preoperative surgical planning, and intra-operative reviewing of 3-D printed models[8]. This 3-D printing strategy could substantially reduce the risk of unpredictable tissue injury during the surgery.

PROTOCOL:

The present study was approved by the ethics committee of Zhongshan Hospital Fudan University (B2016-142R) and all participants gave their informed consent.

1. Diagnosis of the Aortic Anomaly by Symptoms and Acquisition of Imaging Data

1.1. Identify patients who have symptoms such as chest pain, dysphagia, or a blood pressure difference of the upper limbs in out-patient clinic. Exclude patients who may be intolerant of the operation.

1.2. Perform CT angiography in these patients to diagnose Kommerell's diverticulum[8].

2. Segmentation of Regions of Interest

2.1. Import all the CT angiography images into the software in a DICOM format. The resolution of these images was 512 × 512 pixels, and the slice thickness was 1 mm.

2.1.1. Double click the patient case from case library and open it.

2.1.2. Select the DICOM series and click **Model Recon** to open the model recon page.

2.2. Have an engineer and a team of cardiac surgeons review the DICOM formatted raw data to identify key anatomic features and region of interest (ROI).

2.3. Use gray value-based thresholding to segment the ROI.

2.3.1. Click the **Threshold Segmentation** button and adjust the threshold range for the vascular mask. The default range is between 226 to 3071.

2.3.2. Click the **Confirm** button for threshold segmentation and the vascular mask will show in the object list. Click the **Recon** button from the right of the mask and the 3-D vascular mask will be reconstructed and shown in 3-D viewer.

2.3.3. Click the **Threshold Segmentation** button and adjust the threshold range for the trachea mask. Click the **Marquee Segmentation** button to limit the region of interest to the mediastinum and the lung. The default range is between -1024 to -520.

2.3.4. Click the **Mask Edit** button and erase the connection between the trachea and the lung.

2.3.5. Click the **Region Grow** button and select a seed by clicking any point/pixel at the mask in any one of the 2-D viewers. Check and confirm that the region grows as result, and that the trachea mask will show in the object list.

2.3.6. Click the **Recon** button on the right of the mask, and the 3-D trachea will be reconstructed in the 3-D viewer.

2.4. Save the ROI as masks for 3-D reconstruction.

3. 3-D Reconstruction of the ROI

3.1. Adopt the gray value interpolation algorithm to calculate the surface mesh of the 3-D model. Make the surface a triangle to match the outmost voxels of the mask.

3.2. Click the **Export** button to export the 3-D model as an STL file.

3.3. Place the model on the center of the building platform. Orient the model by aligning the tangent of the vessel centerline at its extremity to be parallel to the Z axis of the building platform. Supports were automatically generated to the overhangs using the default parameters.

3.4. Click the **Slice** | **Save** to save as a file ready for 3-D printing.

4. 3-D Printing

4.1. Perform stereolithographic printing with a 3-D printer. Use the following parameters: a slice distance of 1 mm, a resolution of 512 × 512 pixels, a building layer thickness of 0.1 mm, and a laser spot diameter of 80 µm.

4.2. Use ultraviolet light at 405 nm to harden the photosensitive resin by scanning the contours sliced by the software. The ultraviolet light laser speed is 3 m/s.

Note: When one slice of the digital 3-D model was built, the building platform went up 0.1 mm for the next slice. The physical model was built layer by layer. The next layer was formed on top of the previous layer. The 3-D physical model was built layer by layer in this way.

5. Preoperative Planning and Intraoperative Review Using 3-D Printed Models

5.1. Before the surgery, have surgeons make detailed and accurate surgical plans for each patient by learning the 3-D printed models.

5.2. During the surgery, place the 3-D printed models in the operation room and have a nurse hold them. The anatomic details were reviewed by surgeons during the vascular location and separation.

Note: The surgical treatment included resection of diverticulum and reconstruction of aortic branches. The impregnated woven polyester tube graft was applied to replace the resected aorta[1-3,9]. All patients were sent to cardiac surgery intensive care unit after surgery.

REPRESENTATIVE RESULTS:

Acquisition of CT angiography images, digital modeling and 3-D printing were all done in a hospital. Two hours were spent to get the 3-D model from the CT angiography image ready for the 3-D printing. Using the procedure and 3-D printer here, a patient-specific 3-D physical model can be sent to physicians quickly and the surgical decision can be made in time. The workflow from acquisition of CT angiography data to 3-D printing was shown in **Figure 1**. From the coronal plane (**Figure 2A**), the transverse plane (**Figure 2B**) and the sagittal plane (**Figure 2C**), the CT angiography image was reconstructed into a 3-D model (**Figure 2D**). The anatomic relationship between aorta and tracheal was displayed along the Y-axis (**Figures 3A-3D**).

Figure 1. Workflow from CT angiography to 3-D models

Figure 2. Processing of CT angiography data in coronal plane (A), transverse plane (B) and sagittal plane (C). (D) The reconstructed CT angiography data was obtained.

Figure 3. Reconstructed 3-D aorta and trachea model was displayed along Y-axis in the coronal plane (A), transverse plane (B) and sagittal plane (C). (D) The reconstructed CT angiography data was obtained.

DISCUSSION:

Congenital aortic anomalies comprise a rare spectrum of cardiovascular diseases, which often show complex aortic anomalies. Medical imaging, such as CT and MR, are required to elucidate complex aortic arch anomalies, the abnormal branching pattern, their relationship with the trachea and the esophagus, and other associated pathologies. Both CT and MR angiography can provide 2-D information of aortic vessel locations. With 3-D digital reconstruction of 2-D imaging, the anatomical relationship of the aortic vessels can be defined further. However, it is not sufficient to provide a clear view of realistic anatomical structure for surgeons. Kommerell's diverticulum, a rare congenital aortic anomaly, is difficult to be understood for some surgeons due to the variability and complexity of this disease[1]. Therefore, surgical management of this disease needs to be optimized.

The workflow described here includes diagnosis based on imaging data, partitioning the regions of interest, constructing digital 3-D models, printing the 3-D models, preoperative planning and intraoperative reviewing. CT is a common imaging modality for diagnosis of aortic anomalies before surgery. Due to its submillimeter and excellent spatial resolution, CT is commonly used for 3-D printing. Although MR images can also be used for 3-D modeling in some cases, the spatial resolution of MR is generally lower than that of CT. Based on CT datasets, segmentation can convert the anatomical information of the ROI into a patient-specific digital 3-D model. The source of the DICOM data, the complexity of the anomaly, and the operator experience with the software may greatly influence the time required for image segmentation. Moreover, surgeons are also necessary to guide the choice of the ROI in the segmentation procedure. Hence, a team involving surgeons, radiologists and engineers meet to have a discussion before surgery for efficient performance. The rapid diagnosis and in-hospital printing can save time for patients, especially for those who suffered from an emergent dissection or rupture[11]. Therefore, an in-hospital 3-D printing lab is necessary to be established for efficient workflow.

For fellows and residents, even for attending surgeons who have few experiences to perform surgery on complex aortic anomaly, a printed 3-D model could be used to help understand the complex abnormality. A printed model 3-D is a valuable teaching and training tool for easy access to actual anatomical specimens and help flatten the learning curve. They can also serve as an effective tool for communication with patients and their families during the pre-operative counseling.

Although the physical printed 3-D model is helpful for surgeons to understand the anomaly intuitively, it could also allow surgeons to practice the planned operation on the model. Therefore, novel materials should be applied in the 3-D printing to mimic the natural tissue.

Collectively, the printed 3-D model provides an intuitional means of viewing and understanding the patient's complex aortic anatomy. It can help determine a personalized surgical process for the Kommerell's diverticulum and reduce the potential risk of injury.

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DISCLOSURES:

The authors have nothing to disclose.

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Figure 1

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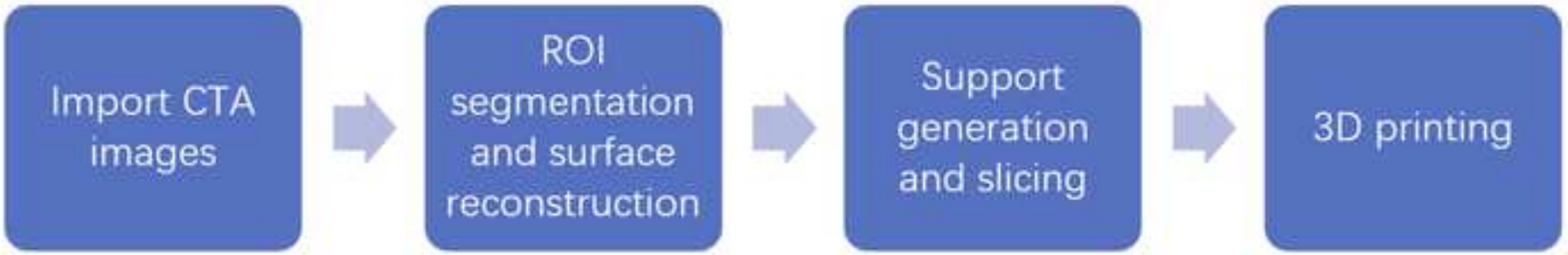

Figure 2

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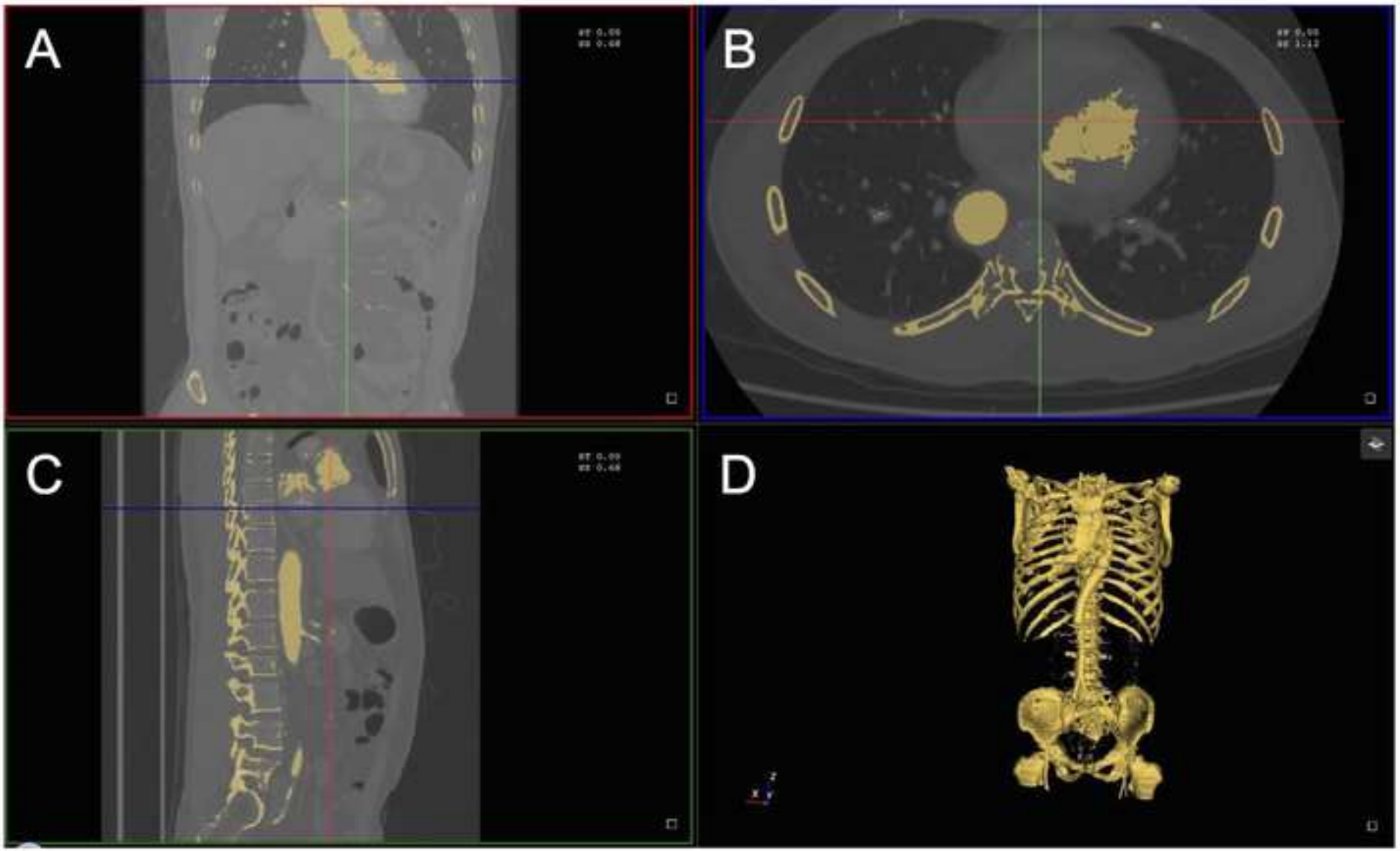

Figure 3

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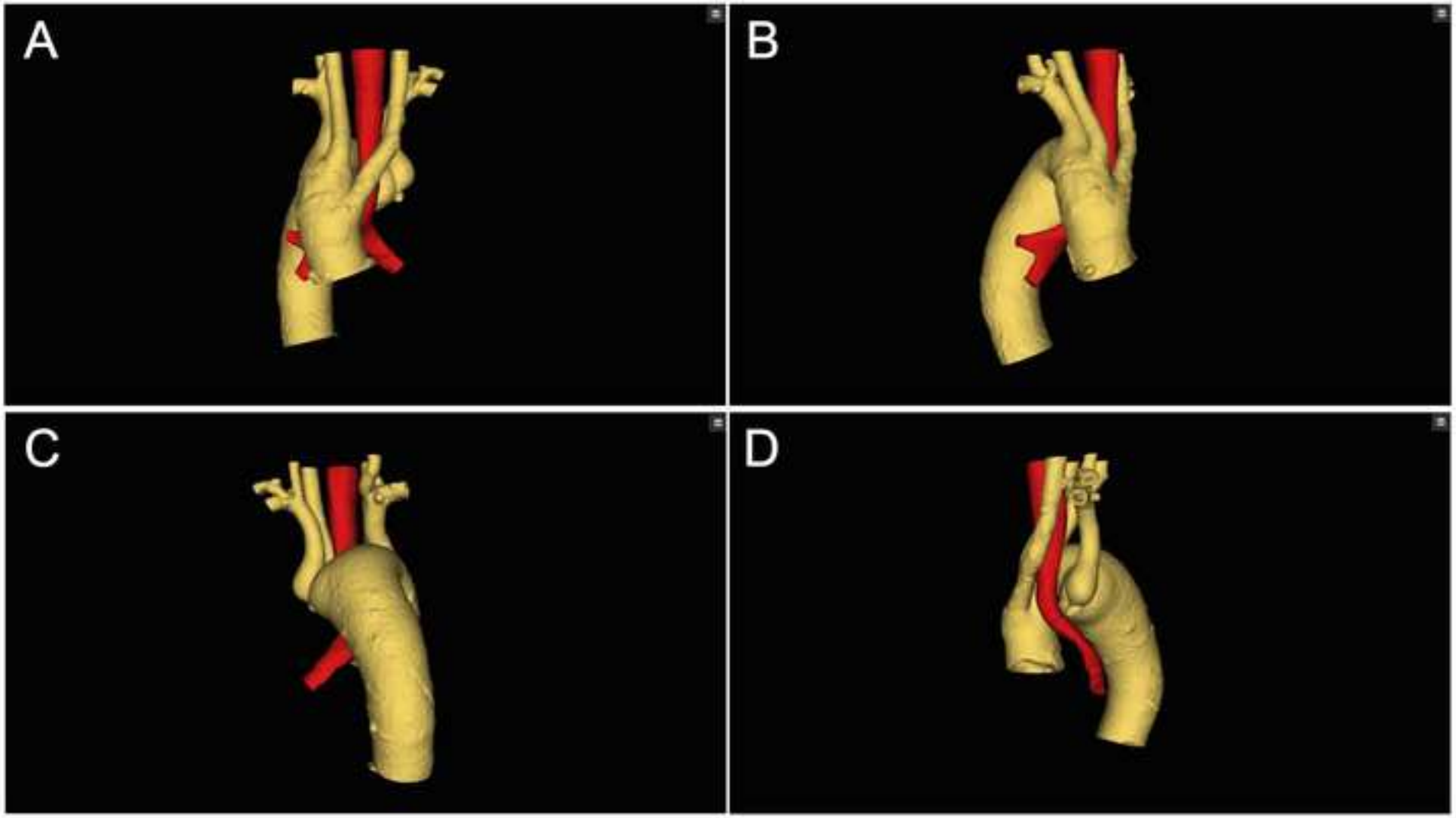

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Name of Material/ Equipment	Company	Catalog Number	Comments/Description
3D printer	Meditool Enterprise Co., Ltd		For 3D printing
Chaos Version 2.0	Meditool Enterprise Co., Ltd		For 3D segmentation and reconstruction

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We would like to submit the revised manuscript entitled "*Three-Dimensional Printing for Surgical Management of Complex Aortic Anomaly*" (Manuscript ID: JoVE58175R2). We wish it to be considered for publication in *JoVE*. No conflict of interest exists in the submission of this manuscript and is approved by all authors for publication. I promise on behalf of my co-authors that the work described has neither been published nor submitted for publication elsewhere.

We highly appreciate the valuable comments and suggestions from reviewers as well as editorial board member during the peer-review process. We have carefully revised the manuscript according to these comments. Our replies and explanation point-to-point to each of the comments are given as below and the changes were highlighted in red in the manuscript.

Sincerely,

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Editorial comments

Comment 1: Please copy-edit the manuscript as there continue to be significant grammatical errors affecting the clarity of the manuscript.
Reply 1: We copy-edit the manuscript again.

Comment 2: Please upload the revised Figures 2-3 with the panel labels.
Reply 2: We feel sorry for the mistake. We uploaded the revised Figure 2-3 with the panel labels.

Comment 3: Additional comments are in the attached manuscript.

Reply 3: We appreciate the comment. We replies the comments and revised accordingly in the manuscript.

Three-Dimensional Printing for Surgical Management of Complex Aortic Anomaly

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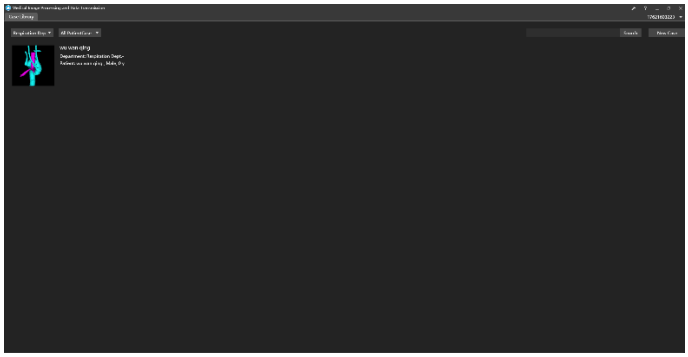
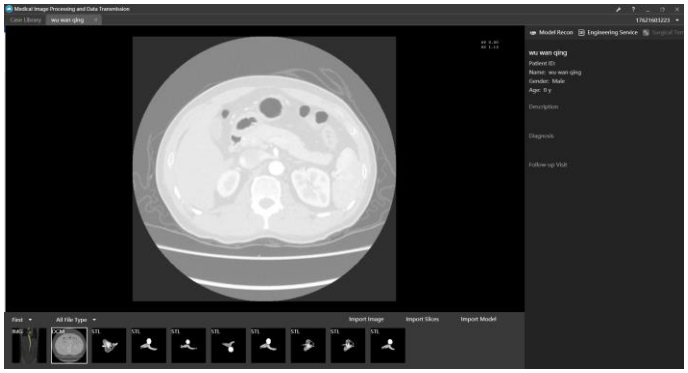
Supplementary materials

The user interface of the software for digital reconstruction was presented as below.

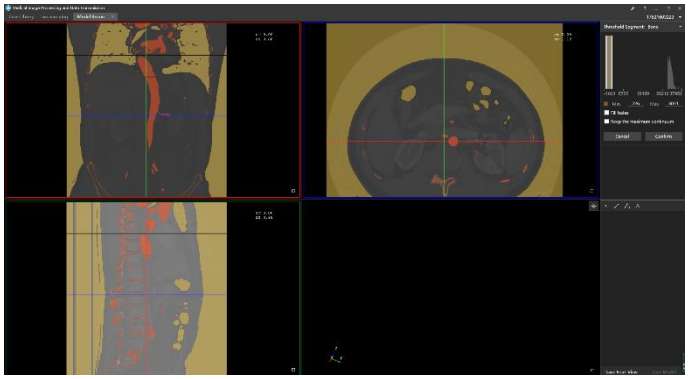
Step1. Double click the patient case from case library and open it:



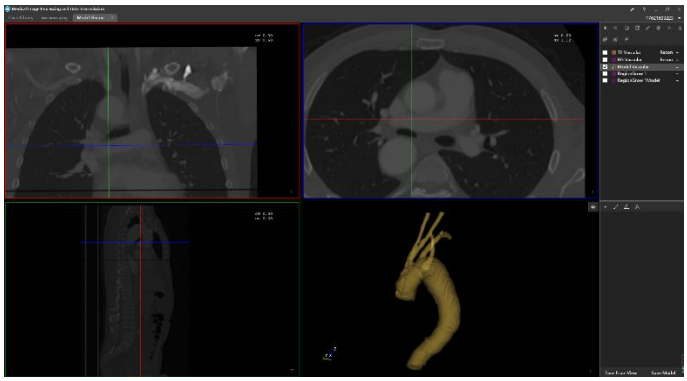
Step2: Select the DICOM series and click “Model Recon” to open the model recon page:



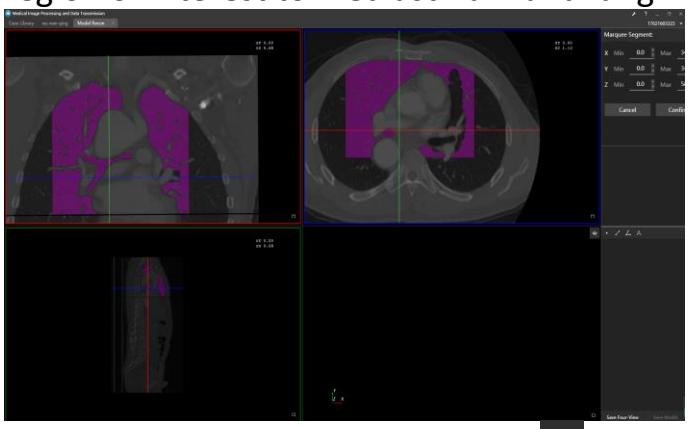
Step 3: Click “Threshold Segmentation” button  and adjust the threshold range for vascular:



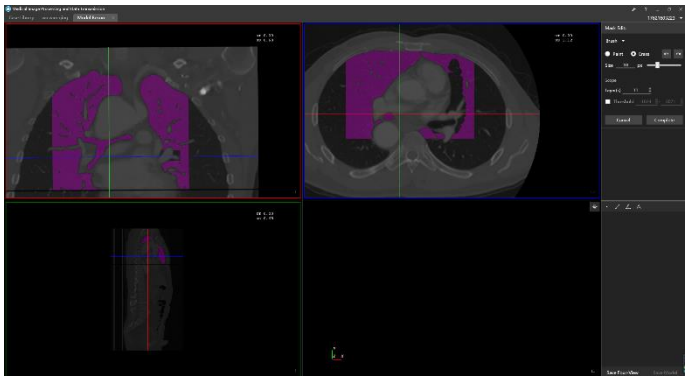
Step 4: Click “Confirm” button for threshold Segmentation, the vascular mask will show in the object list, click “Recon” button from the right of the mask, the 3D vascular will be reconstructed and shows in 3D viewer.



Step 5: Click “Threshold Segmentation” button  and adjust the threshold range for trachea, click “Marquee Segmentation” button  to limit the region of interest to mediastinum and lung:



Step 6: Click “Mask Edit” button  and erase the connection between trachea lung:



Step7: Click “Region Grow” button  and select seeds from the 2D viewers. Check and confirm the region grow result, the trachea mask will show in the object list, click “Recon” button in the right of the mask, the 3D trachea will be reconstructed in 3D viewer.

Step8: check the checkbox of vascular and trachea from the object list, both vascular and trachea will show in 3D viewer. Uses can change the color and opacity of the vascular and trachea by click the color icon.