Perioperative Echocardiography Training: A Role for Ultra-high Resolution Three-dimensional Printed Human Heart Models

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Abstract

Echocardiography is essential for diagnosing and assessing the severity of perioperative structural and/or functional heart disease. Yet, educational opportunities to better understand echocardiography-based cardiac anatomy remain limited by the two-dimensional display, lack of anatomic details, variability of heart models, and/or costs and global availability of training. 3D printing using data from patient CT or MRI datasets has been used for creating effective teaching materials, although often it is limited by the resolutions. In this report, we discuss the development of ultra-high resolution 3D printed human hearts using *ex vivo* microcomputed tomography (µCT) and describe its utility for teaching both basic and advanced recommended views by the American Society of Echocardiography.

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A Role for Ultra-high Resolution Three-dimensional Printed Human Heart Models

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Abstract

Echocardiography is essential for diagnosing and assessing the severity of perioperative structural and/or functional heart disease. Yet, educational opportunities to better understand echocardiography-based cardiac anatomy remain limited by the two-dimensional display, lack of anatomic details, variability of heart models, and/or costs and global availability of training. 3D printing using data from patient CT or MRI datasets has been used for creating effective teaching materials, although often it is limited by the resolutions. In this report, we discuss the development of ultra-high resolution 3D printed human hearts using *ex vivo* micro-computed tomography (µCT) and describe its utility for teaching both basic and advanced recommended views by the American Society of Echocardiography.

Keywords

3D printing; medical education; echocardiography; diagnostic ultrasound; diagnostic imaging

Introduction

Echocardiography is essential for diagnosing and assessing the severity of perioperative structural and functional heart disease.[1-3] Educational opportunities to better understand echocardiography-based cardiac anatomy and pathophysiology during formal cardiology, anesthesiology, and surgical training programs have traditionally been relegated to textbooks and/or online digital resources. Yet, these often fail to convey a full appreciation of the complex three-dimensional (3D) human cardiac anatomies. As a result, 3D-based simulators are becoming widely accepted. However, while they seem accurate and adequate, these simulators often rely on handcrafted models or CT datasets which lack the structural details and anatomic variability routinely seen in clinical practice.[4]Today, gross cadaveric heart dissections are becoming limited for financial, logistical, and social or cultural barriers in some countries.

More recently, 3D printing of anatomic models, using data from scanned images, has been leveraged for creating effective teaching materials.[5-7] At the same time, advances in imaging technology allow for higher resolution datasets and translate directly into higher resolution computational 3D modeling with unprecedented anatomic details.[8,9] 3D printed human hearts[6,10], digital images, and virtual images are being created using cardiac magnetic resonance imaging (cMRI), computed tomography (CT), and echocardiographic imaging, [6 10]yet these imaging technologies typically lack the resolutions to accurately represent atrioventricular valvular and subvalvular anatomy essential for advanced understanding of cardiac anatomy and surrounding structures.[5,11]

Finally, timely care delivery and productivity is often prioritized in the cardiac operating room, leaving trainees with few and sporadic opportunities for adequate perioperative echocardiography training. Currently there are many other reasons why trainees across multiple disciplines do not have optimized opportunities to learn the advanced perioperative cardiac anatomy and pathology required for nuanced care delivery during cardiac surgery, electrophysiologic ablation therapy, and intracardiac catheter-based device delivery. Therefore, we developed ultra-high resolution 3D printed human hearts using *ex vivo*microcomputed tomography (µCT) to teach basic and advanced American Society of Echocardiography (ASE)-recommended cardiac ultrasound views.[1]

Methods

Data acquisition and 3D modeling

For several decades, the Visible Heart® Laboratories at the University of Minnesota have received gifted organs for research. To date, we have perfusion-fixed more than 650 human hearts, utilizing this rich library for generating education models for echocardiography training. Briefly, following consent from donors and/or donor families, fresh human heart specimens not suitable for orthotopic transplantation were procured by LifeSource (Minneapolis, MN, USA) and donated to the Visible Heart®· Laboratories. In general, within hours of explantation, the great vessels of these hearts were cannulated and then perfusion-fixed with 10% formalin for at least 24 hours to preserve an approximation of the end-diastolic state.[12] Prior to imaging, each specimen was rinsed for a minimum of 12 hours to remove any remaining formaldehyde.

Next, we performed µCT scans with 100µm resolution (X3000 CT, North Star Imaging, Rogers, MN, USA) of the specimens, and imported anonymized datasets into the post processing software Mimics® Innovation Suite (Materialise NV, Leuven, Belgium) to create high-resolution computational 3D models using automatic, semi-automatic, and manual segmentation methods.[10] The cardiac walls, vessels, and valves were typically segmented separately to create a mesh focused on each specific structure(s). Next, the resulting 3D models were exported as stereolithography (STL) files.

3D Printing

Models were edited accordingly and prepared for 3D printing using 3-Matic (Materialise NV). Typically, the surfaces of the model were somewhat smoothed and any errors/gaps in the models were fixed.

Echocardiography Views Models

We identified echocardiographic planes to represent different views as recommended by ASE guidelines.[1] For each computational model, echocardiographic planes were digitally created and incorporated into a heart model under the guidance and consensus of several physicians trained and certified in advanced clinical echocardiography. We labeled the models and created reciprocal holes (3.2 x 6.2 mm) to accommodate magnets. Next, sets of magnets (3 x 6 mm) where embedded as a means to hold corresponding pieces together.

We then printed the models to scale using a variety of 3D printers and 3D printing materials including an H350 Selective Absorption Fusion powder bed printer with High Yield PA11 Nylon 11 (Stratasys, Eden Prairie, MN, USA), a MakerBot Method X printer with white Tough Polylactic Acid (PLA) (MakerBot, New York City, NY, USA), a uPrint with Acrylonitrile Butadiene Styrene (ABS) (Stratasys), and an Ultimaker 3Extended with PolyLite PLA (Ultimaker B.V., Geldermalsen, The Netherlands).

Isolated Valvular Structures

We also printed the mitral and tricuspid valves utilizing a J750 Digital Anatomy printer (Stratasys), using anatomical presets for moderately stiff valve annulus material (blending VeroUltraWhite, TissueMatrix, and Agilus30Clear) and 706B support material.

Results

From the 650+ fixed specimens in our Human Heart Library, we chose to image and generate models from a variety of hearts. These specimens were selected primarily based on how well the cardiac anatomy was preserved following explantation, as well as cardiac disease state. For our initial educational purposes, we scanned, modeled, and printed models from 4 different human hearts selected from our human heart library (Table 1). The *ex vivo* CT imaging of these specimens provided high-resolution detail of the atrioventricular valves and corresponding subvalvular structures (***Figs. 1,2***). ASE-recommended transesophageal echocardiography (TEE) views ***(Fig. 3)***and transthoracic echocardiography (TTE) Focus Assessed Transthoracic Echo (FATE) views ***(Fig. 4)*** were selected for representation by identifying and matching planes for each generated model (Supplemental Video 1).

The cost of materials to print each heart model ranged between $80-120 USD, the printing time spanned 14-80 hours per model, and the weights of each model were between 250 and 400 g depending on the general quality/durability of the selected material, the 3D printer, and the size of the model. Note that once all models were optimized, the costs and printing times could be reduced. Further, the average cost of each 3D printed valve was $50 USD, and the time required for printing was 8 hours.

Educational Uses

These generated 3D printed cardiac models are readily available to residents, cardiothoracic anesthesia (CTA) fellows, and attendings in each cardiac operating room at the University of Minnesota Medical Center. At our institution, these models are routinely used for teaching residents and CTA fellows about basic and advanced echocardiographic views, cardiopulmonary bypass cannulation strategies, and valvular pathology and planned interventions (Figs. 5,6) in both normal and pathological states (Fig. 7).

We also share the ready-to-print 3D models with the public through the free-access Atlas of Human Cardiac Anatomy website (http://www.vhlab.umn.edu/atlas/). We are committed to our mission to provide world-class educational materials for anyone, anywhere.

Discussion

We described a novel computational methodology using µCT to 3D print ultra-high resolution human hearts in the form of ASE-recommended TEE and TTE FATE views to facilitate advanced understanding of perioperative echocardiography. We envision using these models to facilitate accurate, high-resolution 3D visualization and tactile feedback to accelerate memorizing absolute and relative cardiac anatomy. While formal studies comparing traditional methods for teaching perioperative TEE with our 3D printed human hearts are forthcoming, we have implemented this teaching tool as an adjunct to be used in the operating and procedure rooms for instructing anesthesia residents and cardiothoracic anesthesia fellows.

We consider that visualizing cardiac anatomy, both absolute and relative, in various 3D perspectives can improve spatial recognition and understanding while learning perioperative echocardiography.[13,14] Although published data are sparse, Radzi and colleagues used CT imaging to generate 3D printed hearts as means to teach cardiac anatomy.[13] Limited by their imaging technologies, this group reported difficulties while segmenting the mitral and tricuspid valves. In a recent comparative study including 153 medical students, Salewski and coworkers reported a significant advantage in using 3D printed heart models when compared with conventional educational resources, despite using CT image-generated models from the Resuscitative TEE Project that lacked atrioventricular valves.[6] It should be noted that Ochoa et al. reported no benefit in using low-resolution generic plastic 3D models sliced to represent echo views; this is contradictory to results from other groups, and perhaps the result of the smaller group size of only 20 medical students surveyed.[15]

Building on this prior work, we used µCT technology to accurately represent the valvular and subvalvular anatomies of the atrioventricular valves. With our ability to represent cardiac anatomy and pathology in ultra-high resolution 3D models, including the atrioventricular valves and associated anatomy, we are confident that these educational tools can significantly accelerate cardiac anatomic understanding in a safe and predictable manner. Moreover, by generating multiple unique prints of our ultra-high resolution heart models to represent each 2D plane of the ASE-recommended TEE and FATE TTE views, we have effectively transferred relatively low-resolution two-dimensional images from the echocardiography machine into ultra-high resolution, low cost, durable, and portable models that can be manipulated and studied, again and again in a safe and predictable environment within or outside the operating room. Notably our generated high-resolution cardiac models can be printed using a variety of 3D printers employing a range of materials; this should allow others to adjust materials, weights, and time of 3D printing relative to the system available. By using these types of files that are compatible with a range of 3D printing technologies, we plan to make possible unrestricted and equitable access to our high-resolution 3D cardiac echo models.

We have identified various limitations in using our cardiac models to teach anesthesia residents and cardiothoracic anesthesia fellows. Our current models do not include extended portions of the great vessels. Thus we have combined *in vivo* cMRI or CT images with our *ex vivo* μCT images in an effort to add great vessel anatomies.[16] Furthermore, we have printed the myocardium and valves with rigid materials that do not accurately represent the dynamics of the cardiac anatomies. We are currently experimenting with printing the various cardiac structures including the myocardium, valve annuli, leaflets, and chordae tendinea in more pliable materials that allow learners to experience valve and leaflet positions. Finally, we need to generate high-resolution models with valves representing all phases of the cardiac cycle, work that is ongoing by our team.

Conclusions

Representing the human heart by ultra-high resolution 3D models, printed to display ASE-recommended echocardiographic views, is now feasible by using μCT imaging of perfusion-fixed human heart specimens. In so doing, we have generated a library of printed hearts as a unique educational tool designed to accelerate, rapidly and safely, the understanding of absolute and relative human cardiac anatomy and pathology, especially related to gaining advanced appreciation of clinically employed perioperative echocardiography.

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Figure Legends

Figure 1 . 3D printed models of HH 229. Slice on the left represents a transthoracic echocardiography (TTE) parasternal long-axis view, and that on the right represents the transesophageal echocardiography (TEE) mid-esophageal and transgastric long-axis view. Ao=aorta; LA=left atrium; LV=left ventricle; LVOT=left ventricular outflow tract; RV=right ventricle.

Figure 2. 3D printed model of the tricuspid valve of HH 223. (A) Model printed in clear material as viewed from the atrium with leaflets labeled and the moderator band marked with red arrow. (B) Model printed using multiple colors and materials and rotated to appreciate the subvalvular apparatus. Yellow, tricuspid annulus; transparent, mitral leaflets; blue, chordae tendinea; pink, papillary muscles.

Figure 3. High-resolution fusion powder 3D printed heart models representing the transesophageal echocardiography (TEE) American Society of Echocardiography (ASE)-recommended views. Each row represents two corresponding planes on each model that have been labeled accordingly. LAX=long-axis; RV=right ventricle; SAX=short-axis; TG=transgastric.

Figure 4. High-resolution fusion powder 3D printed heart model representing the Focus Assessed Transthoracic Echo (FATE) views (A) composed of 8 pieces representing (B) the parasternal long-axis view, (C) parasternal short-axis view, and (D) apical four-chamber and/or subcostal view.

Figure 5. 3D printed models being utilized by trainees within the operating room during a transesophageal

echocardiography (TEE) educational opportunity. (A) transgastric short-axis (TG SAX) view, (B) midesophageal long-axis (ME LAX) view, and (C) four-chamber view.

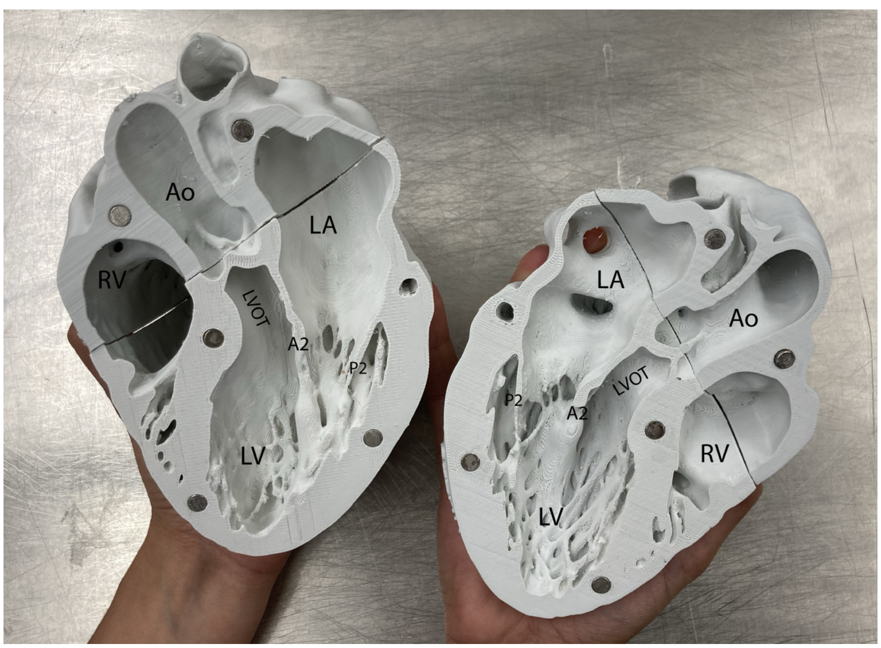
Figure 6. 3D printed model of mitral valve being utilized by trainees within the operating room during a transesophageal echocardiography (TEE) educational opportunity.

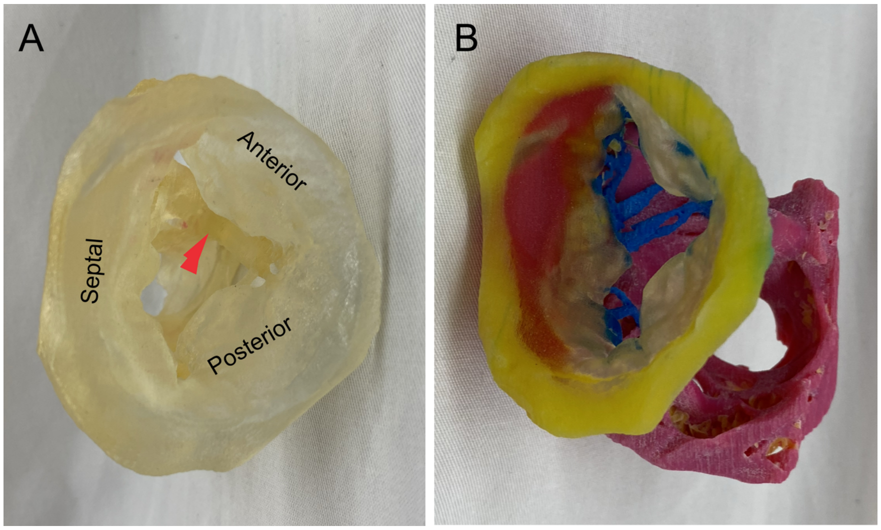
Figure 7. 3D printed models of HH 281. Slice represents a transesophageal echocardiography (TEE) mid-esophageal long-axis view of a heart with severe hypertrophic cardiomyopathy. The left atrium was removed during explantation. (A) Mitral valve, (B) left ventricle, (C) aortic valve, (D) right ventricle, (E) hypertrophic interventricular.

Supplemental Video 1. High-resolution 3D printed human heart model sliced in four-chamber and two-chamber views. The reciprocal pieces are held together by magnets.

Table 1. Human heart demographics and medical history

Human Heart Specimen	Patient Age (yr)	Patient Gender	Medical History
HH103	68	M	Arterial hypertension, diabetes mellitus, atrial fibrillation, atrial septal defect
HH223	56	M	Coronary artery disease, obstructive sleep apnea
HH229	44	F	Arterial hypertension, heart failure
HH281	14	F	Hypertrophic cardiomyopathy

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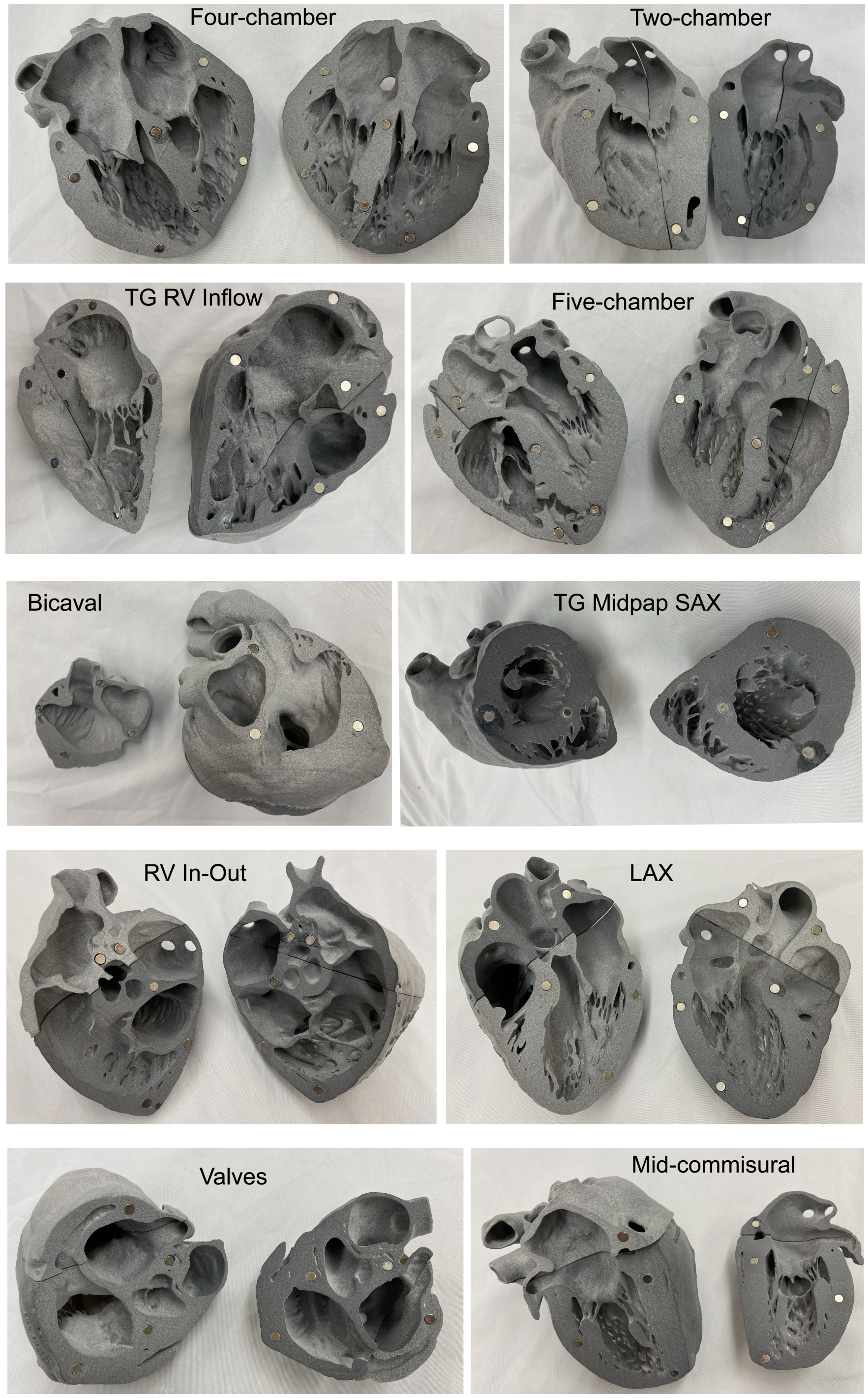
Septal
Posterior
B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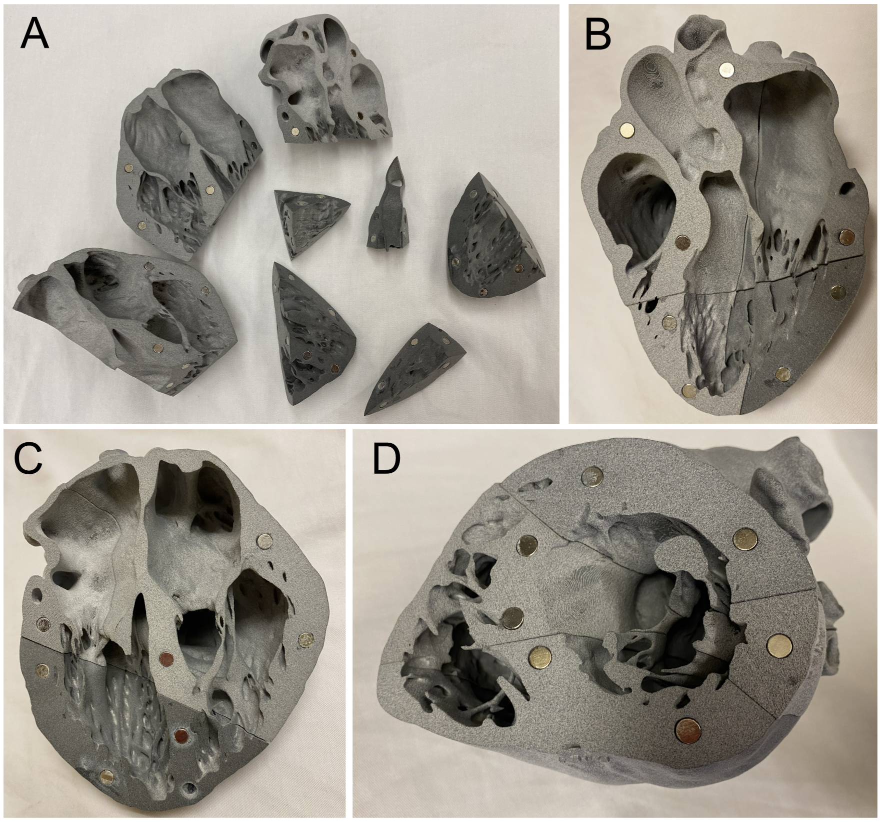
TG RV Inflow
Five-chamber
Bicaval
TG Midpap SAX
RV In-Out
LAX
Valves
Mid-commisural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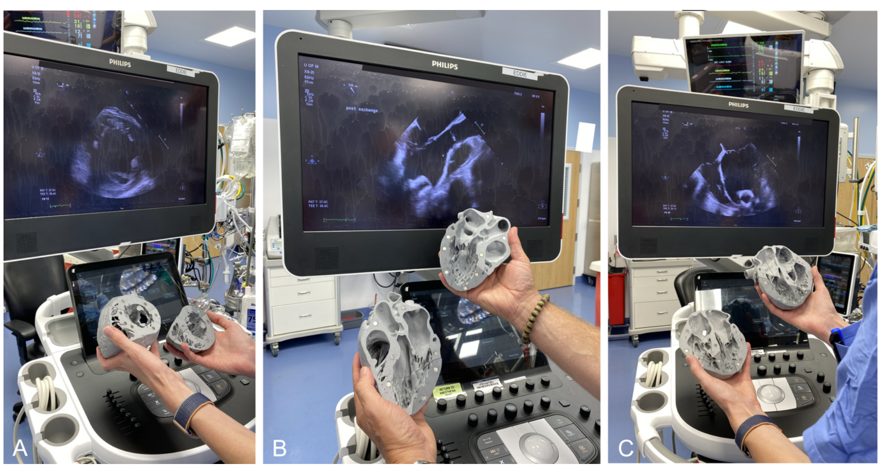
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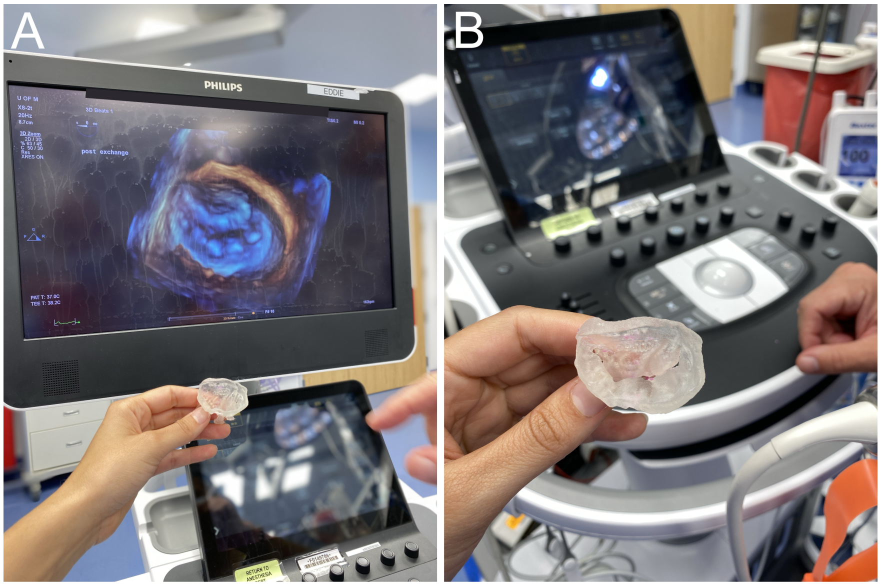
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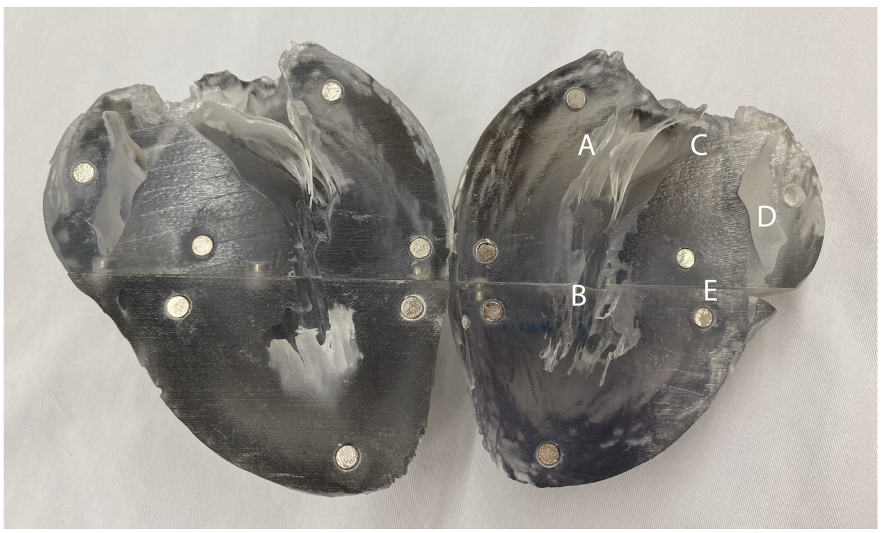
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