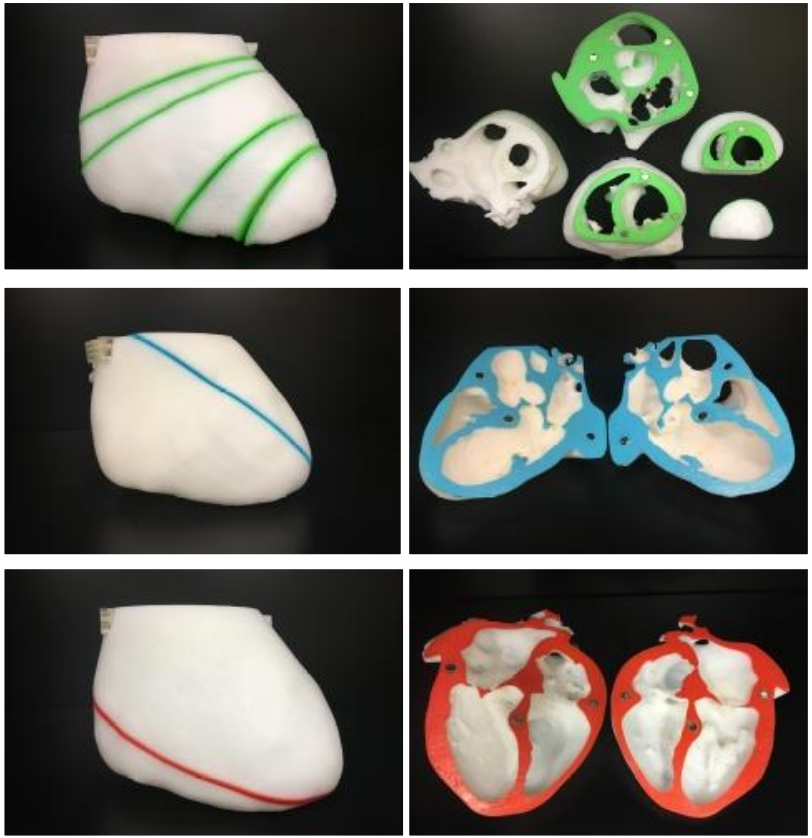
Patient-specific Models

Educational Models & Simulation

Educational Demonstration Models: FOCUS



For ultrasound teaching

Source: Cardiac CT

Segmentation: ITK-SNAP

Post-processing: Meshmixer

Print: Taz 5 + Polylite

Image Credit: Dr. Matthew Bramlet; Jump Trading Simulation and Education Center.

Heart Library

Sponsored by Jump Simulation

Welcome to the 3D Heart Library, a collection of digital reproductions of human anatomic hearts, with a specific area of interest in congenital heart disease. The highly accurate 3D representations of hearts have been created directly from patient MRI data. The goal of the 3D Heart Library is to serve as a platform for sharing, collaboration, and education.

If you are a medical or engineering professional with questions about the 3D Heart Library or are interested in submitting a case study, please complete the contact form on the Jump Simulation website.

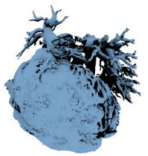
MORE MODELS AND INFO ARE ON THE WAY AS THIS EXCITING NEW COLLABORATION DEVELOPS!

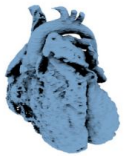
Displaying 56 of 56.

Search

Diagnosis/Condition
- Any -

Segmentation Method
- Any -






Procedural Phantoms: CHD Surgical Training

The Journal of Thoracic and Cardiovascular Surgery
JTCVS

Van Arsdell et al. Three-dimensional printing in congenital cardiac surgery-Now and the future. J Thorac Cardiovasc Surg. 2020;160: 515–519. doi:10.1016/j.jtcvs.2019.12.131

CONGENITAL: CONGENITAL HEART SURGERY: INVITED EXPERT OPINION

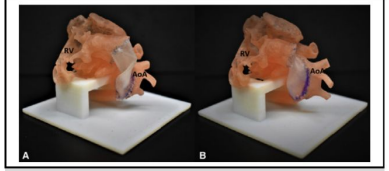
Three-dimensional printing in congenital cardiac surgery—Now and the future

Glen S. Van Arsdell, MD,[a,b] Nabil Hussein, MBChB,[c,d] and Shi-Joon Yoo, MD[c,e]

***Feature Editor's Note**—Dr Van Arsdell and colleagues*

printing. The first is, "the surgeon can decide the surgical plan much as is achieved with intracardiac exploration." The days of the surgeon having to open up the heart and make an on-the-spot decision as to what type of repair to perform are rapidly fading. Now (like musicians) the surgeon (or trainee) can practice beforehand and have a definite plan for the operation.

"The time for learning curves on patients has passed." In the current era of transparency and public



A, Coached versus B, noncoached arch reconstruction in the Norwood operation.

CENTRAL MESSAGE

3D printing is changing the landscape for surgical training and surgical planning in complex congenital heart disease.

See Commentary on page 520.

Procedural Phantoms: CHD Surgical Training

The Journal of Thoracic and Cardiovascular Surgery JTCVS

Van Arsdell et al. Three-dimensional printing in congenital cardiac surgery-Now and the future. J Thorac Cardiovasc Surg. 2020;160: 515–519. doi:10.1016/j.jtcvs.2019.12.131

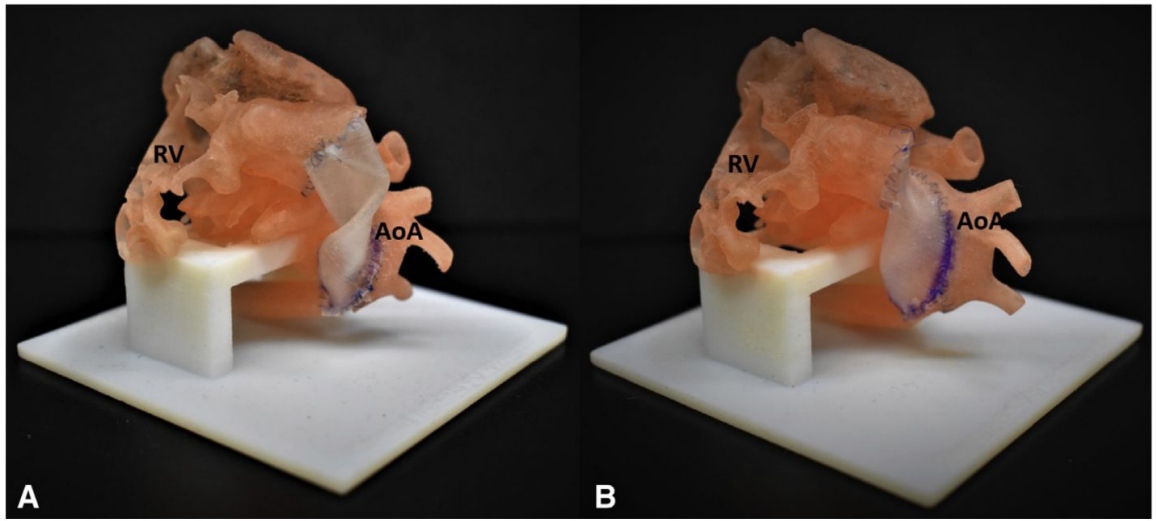
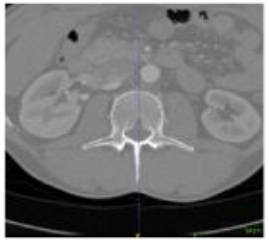


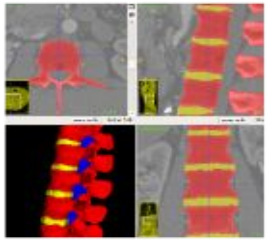
Fig 3. (A) shows a **well coached** Norwood arch reconstruction. The arch will fill nicely, and without obstruction, when pressurized.
(B) shows a **non coached** Norwood reconstruction. Note the inadequate patch size at the proximal end that will result in outlet obstruction.

Procedural Simulation Phantoms

Neuraxial Injection

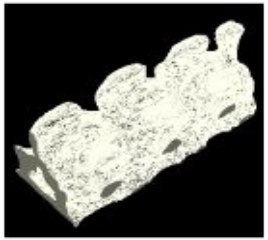


3D Image
CT / MRI / US

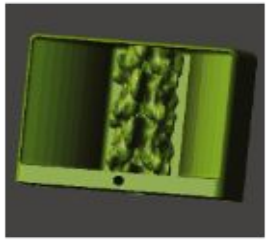


Segmented
Label Map

ITK-snap
3D Slicer

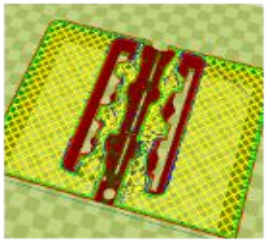


Raw
3D Model



Edited
3D Model

OpenSCAD



Printer
Code

Slic3r

3D Print

FDM
(Taz 5)

Mashari et al. Low-cost three-dimensional printed phantom for neuraxial anesthesia training: Development and comparison to a commercial model. PLOS ONE. 2018;13: e0191664. doi:10.1371/journal.pone.0191664

Jeganathan et al. Use of 3-Dimensional Printing to Create Patient-Specific Thoracic Spine Models as Task Trainers. Reg Anesth Pain Med. 2017. doi:10.1097/AAP.0000000000000580

Procedural Spine Phantom

Simulab (TM)

Spinal & epidural training phantom. Silicone casing. Inner material unknown.

Normal & pathological model (1)

$3500-4000

“Spine Box”

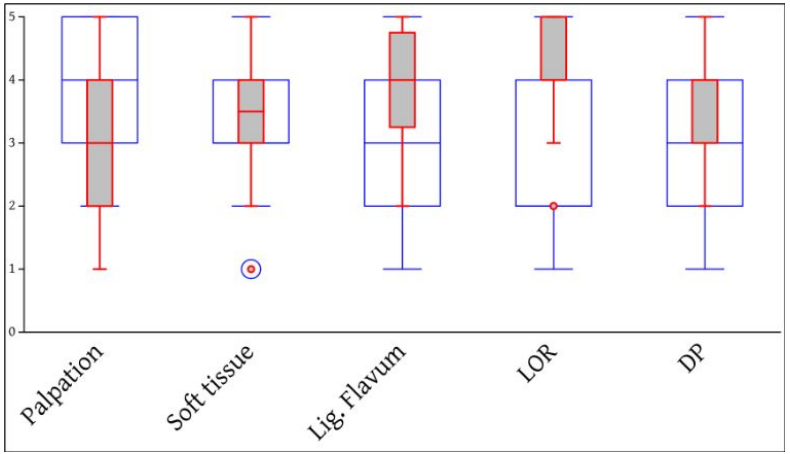
Model generated from CT in public database (Osirix)

Corn-based plastic, boat-sealant silicone, and molded silicone thecal sac, gelatin

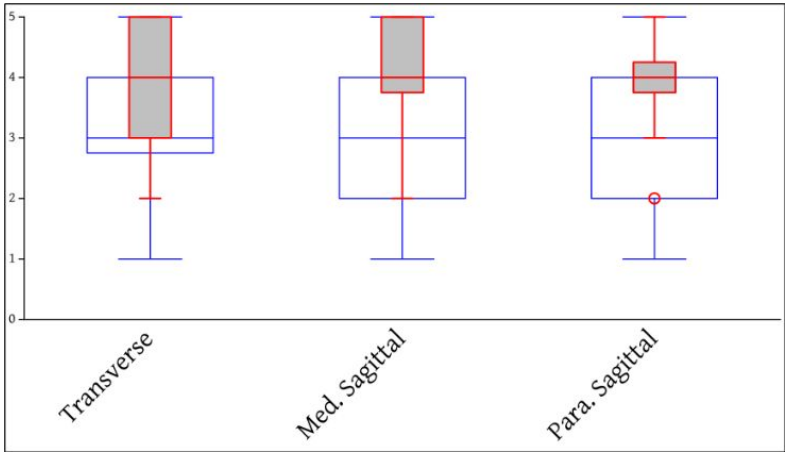
~$250 (including labour costs)

doi:10.1371/journal.pone.0191664

Expert Evaluation: Tactile & US Fidelity (22 Staff Anesthesiologists)



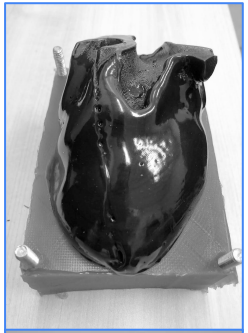
Tactile

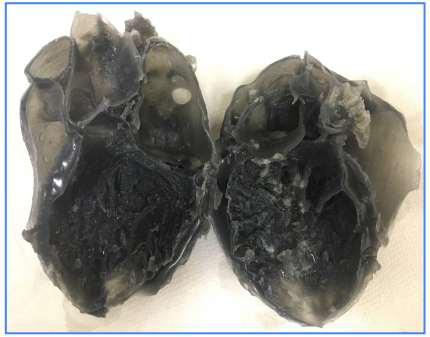


Ultrasound

doi:10.1371/journal.pone.0191664

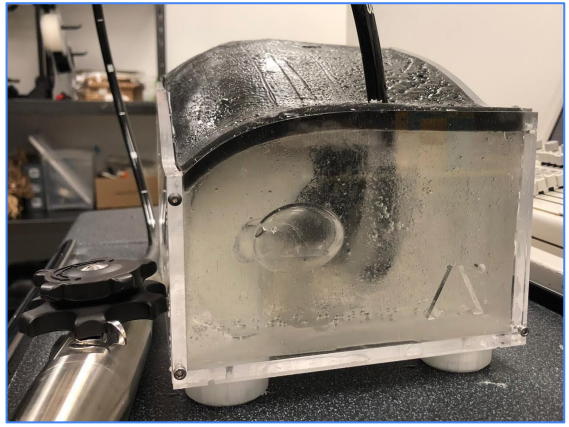
TEE Phantom (Cardiac CT, 3DP, Casting)

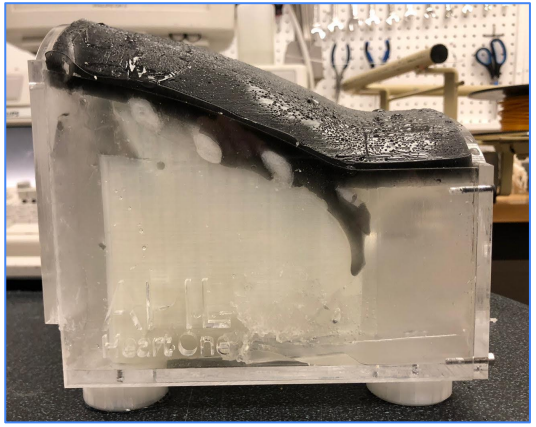


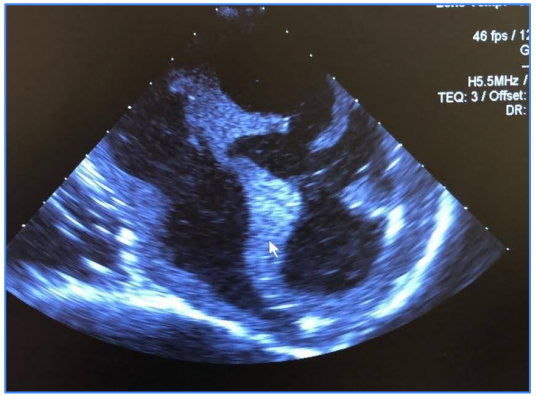


Cardiac CT; ITK-Snap/3D Slicer; Meshmixer; Positive 3D Print (FDM); Silicone Mold; Ballistic gel + graphite heart; Gel wax surround; Silicone cover.
Total cost CAD $1000-1500

Meineri et al. Evaluation of a Patient-Specific, Low-Cost, 3D-Printed TEE Phantom. JCVA. 2021;35: 208–215. doi:10.1053/j.jvca.2020.07.008







TEE Phantom: Acceptable Visual Fidelity

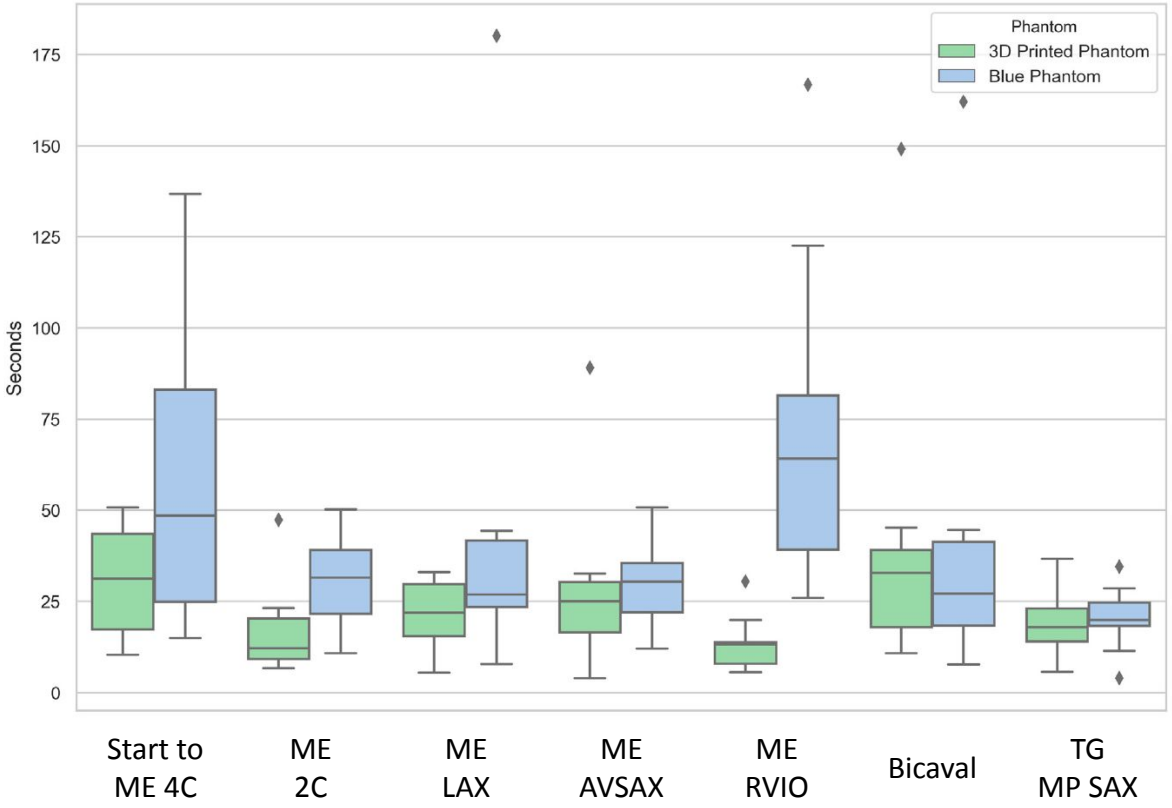
Rating of Each View Proposed Compared With the Same View From a Human Subject on a Likert Scale*

	3D-Printed Phantom	Commercial Phantom	*p*
ME AV SAX	2 (1.5)	2 (1)	NS
ME 4C	3 (1.5)	2 (1)	NS
ME 2C	3 (0.75)	3 (1.5)	< 0.05
TG SAX	2 (1)	3 (0.75)	NS
ME bicaval	2 (0)	2 (1)	NS
ME LAX	3 (0)	4 (1)	NS

1 = not comparable with the equivalent view obtained on a human subject;
5 = equivalent to the view obtained on a human subject.

Meineri et al. Evaluation of a Patient-Specific, Low-Cost, 3-Dimensional–Printed TEE Human Heart Phantom. JCVA. 2021;35: 208–215. doi:10.1053/j.jvca.2020.07.008

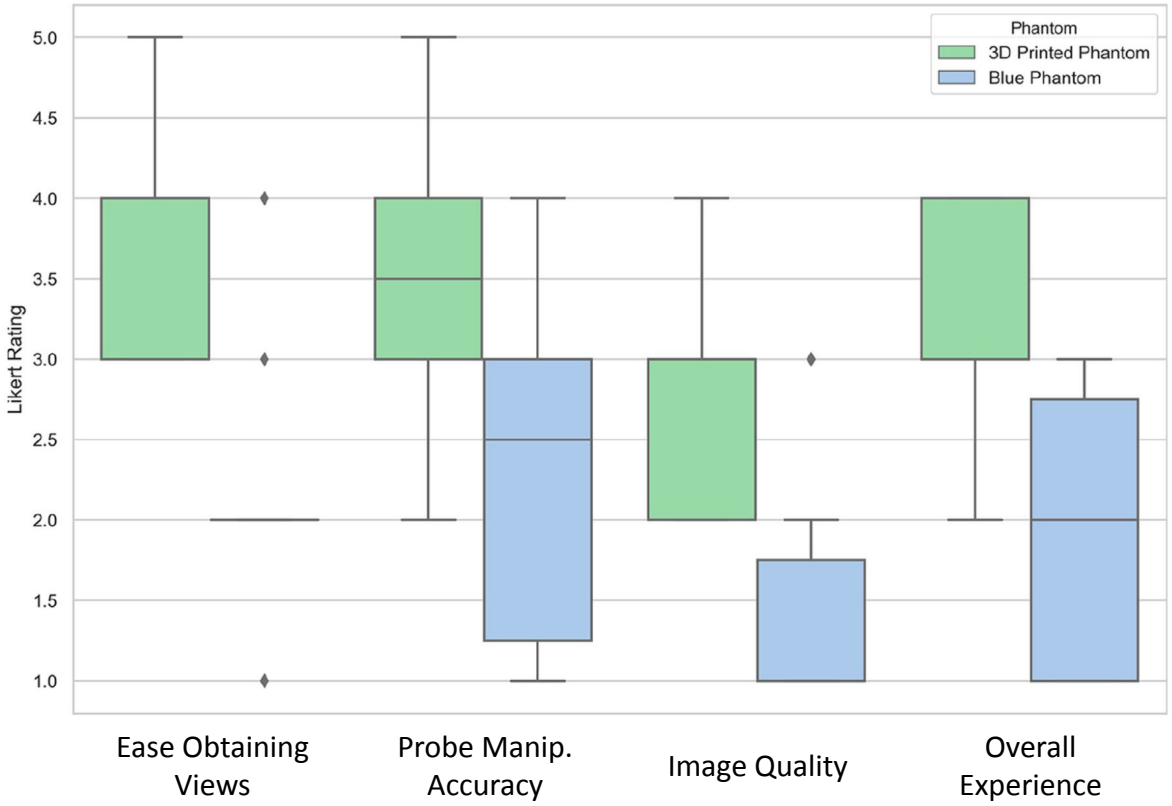
TEE Phantom: Expert Acquisition Time



Phantom
3D Printed Phantom
Blue Phantom

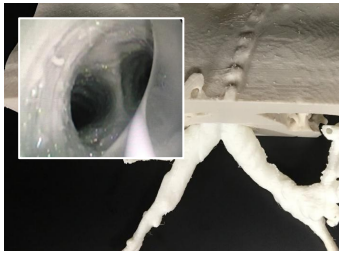
Meineri et al. Evaluation of a Patient-Specific, Low-Cost, 3-Dimensional–Printed TEE Human Heart Phantom. JCVA. 2021;35: 208–215. doi:10.1053/j.jvca.2020.07.008

TEE Phantom: Useability

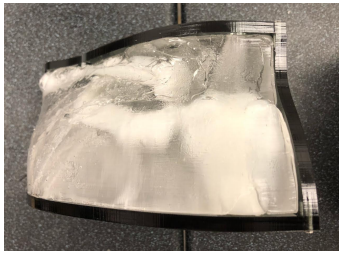


Meineri et al. Evaluation of a Patient-Specific, Low-Cost, 3-Dimensional–Printed TEE Human Heart Phantom. JCVA. 2021;35: 208–215. doi:10.1053/j.jvca.2020.07.008

Custom Fabricated Educational Phantoms



Parotto et al. Evaluation of a low-cost, 3D-printed model for bronchoscopy training. Anaesthesiol Intensive Ther. 2017;49: 189–197. doi:10.5603/AIT.a2017.0035



Peacock et al. Subclavian Central Venous Access (Echogenic). Evaluation in progress.

Ultrasound guided vascular access

Custom Fabricated Educational Phantoms

Greater Range of Models

- Normal variants
- Spectrum of disease
- Rare conditions

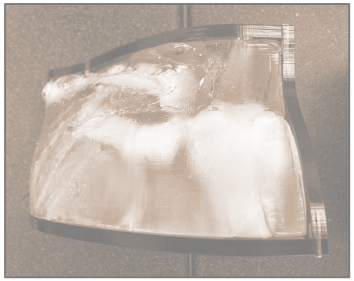
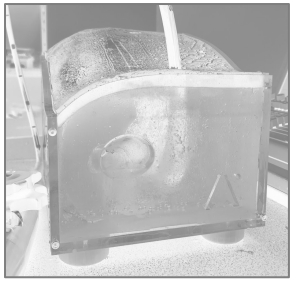
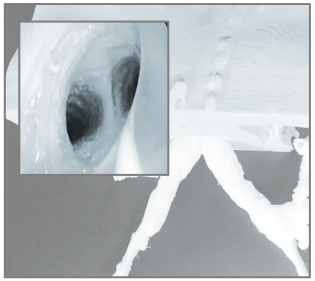
Highly Customizable

- Tailored to learning objectives, educational approach & evidence

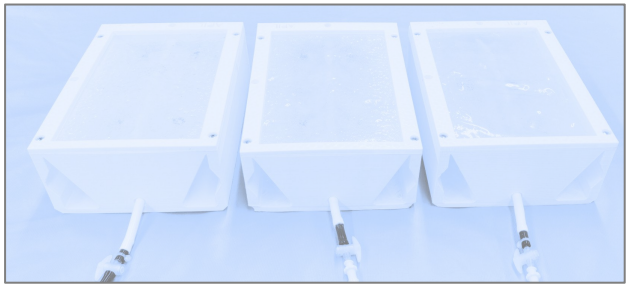
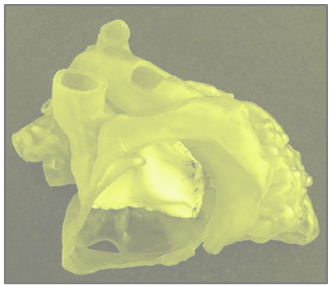
Easy Collaboration

- Growing open source collections

Lower Cost

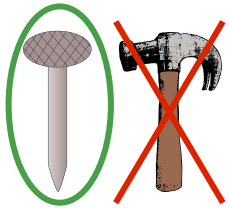




Integration into **evidence-based multi-modal curriculum**

doi:10.1186/s41205-016-0004-x

Procedural Training Phantoms: Development Approach



1. Procedural phantoms should be developed as part of a need-driven curriculum (Nail-First Approach)
2. Identify task elements and steps of the procedure and corresponding learning objectives

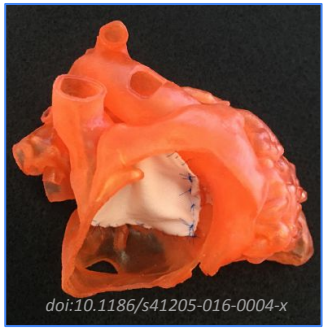
   Set-Up; Positioning; Landmarking; Ultrasound Anatomy; Eye-Hand-Needle Coordination; Tactile Feedback

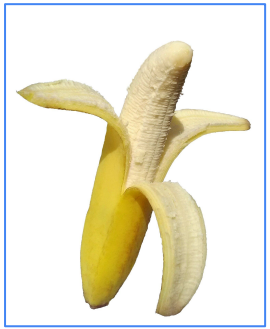
3. Identify learning stages and organize objectives by stage
4. Identify type (tactile, visual, ultrasound) & optimal level of fidelity required for each stage

   Live tissue is not the gold standard!

5. Identify required interactions & corresponding modalities for each stage: 2D, 3D print / Render / VR / AR / Banana / Chicken

   Cost, Accessibility, Usability, Interactions, Storage





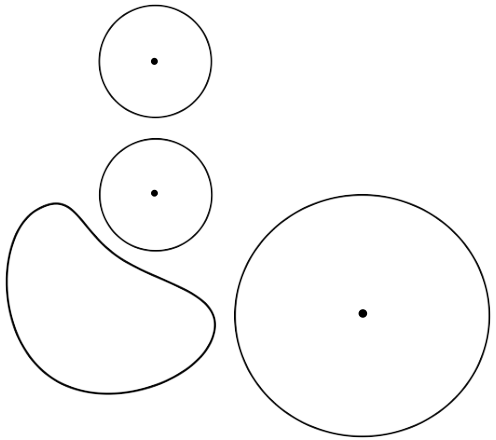
Banana by Filo gèn' cc-by-sa; Chicken by Marco Verch cc-by 2.0

Echo Anatomy Teaching Example:
Combining 2D and 3D modalities

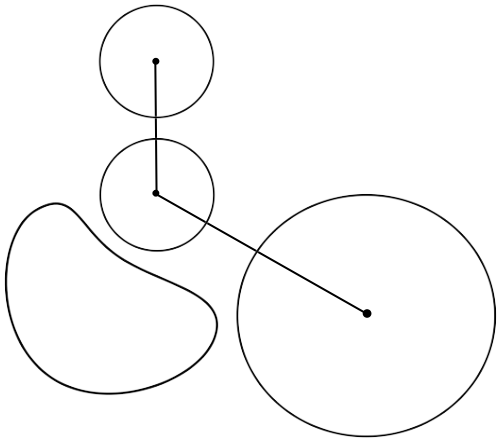
Full version of presentations (with recording and all original media content - cc-by) at
https://github.com/tgh-apil/Presentations/tree/main/2021-ISURA

Heart Base

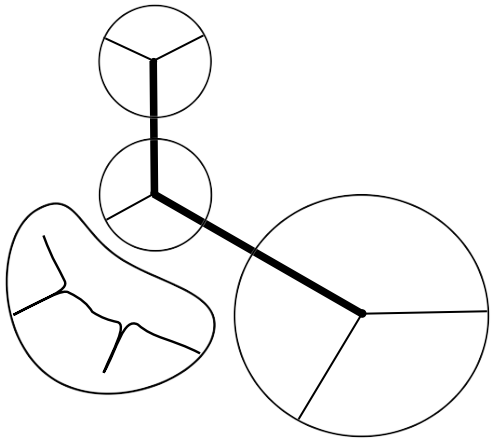
1

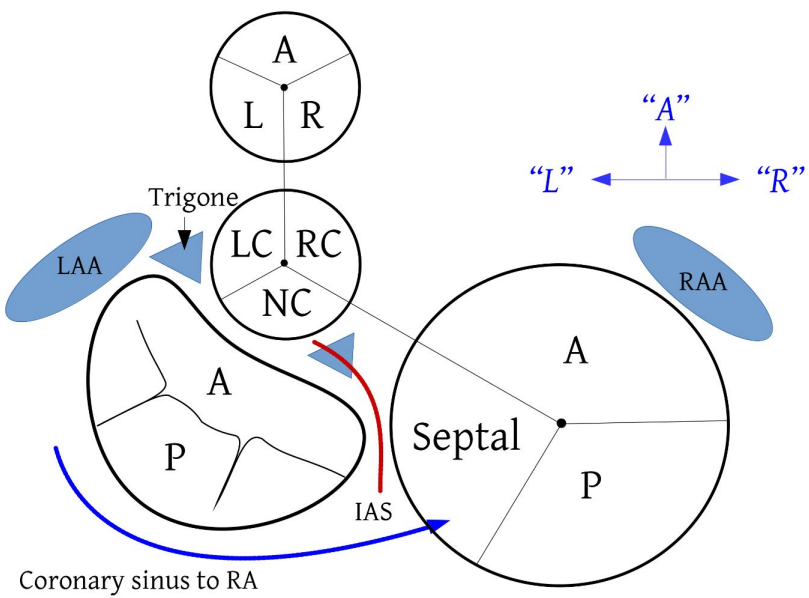


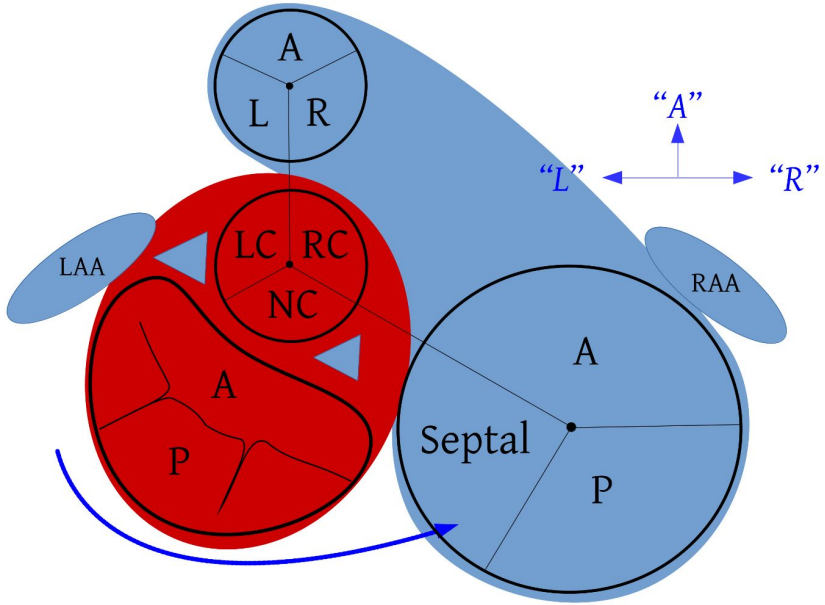
2



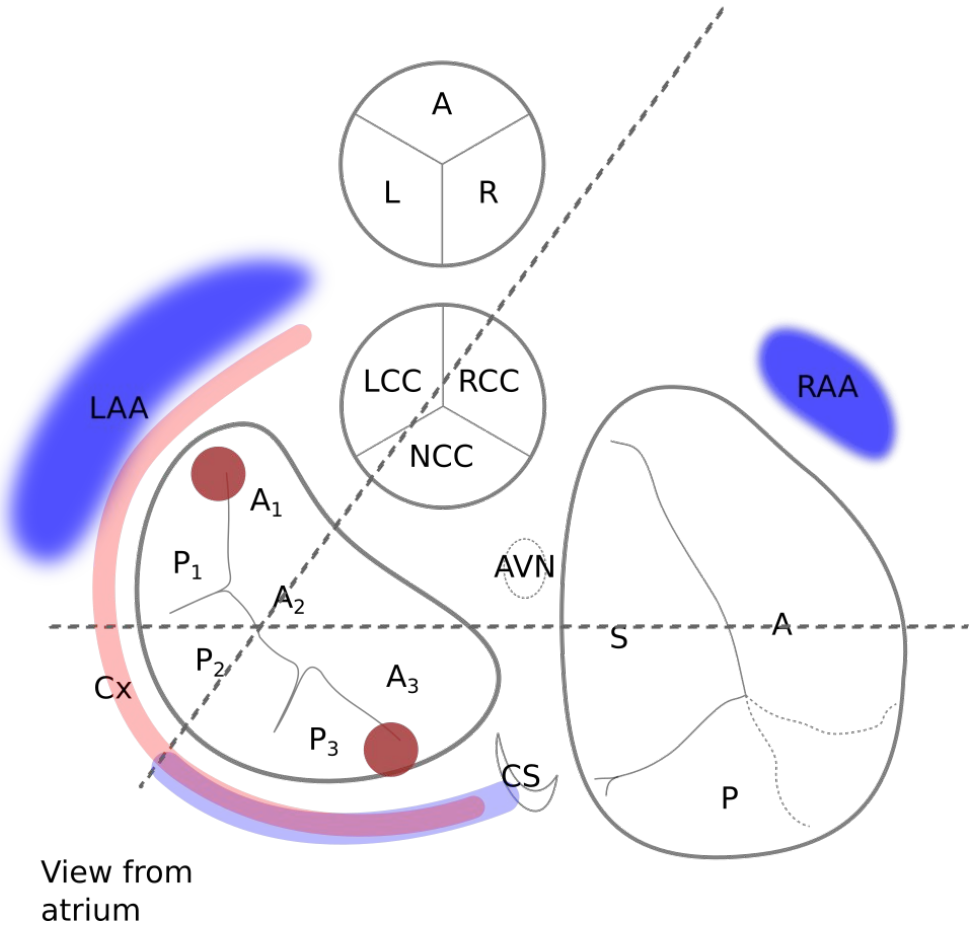
3




A
L
R
Trigone
LC
RC
NC
LAA
RAA
A
P
Septal
A
P
IAS
Coronary sinus to RA
"A"
"L"
"R"


A
L
R
LC
RC
NC
LAA
RAA
A
P
Septal
A
P
"A"
"L"
"R"

CT-based Model: https://skfb.ly/6LGwF



View from atrium

3D Model

Cardiac-gated CT (3DSlicer - FLOSS)

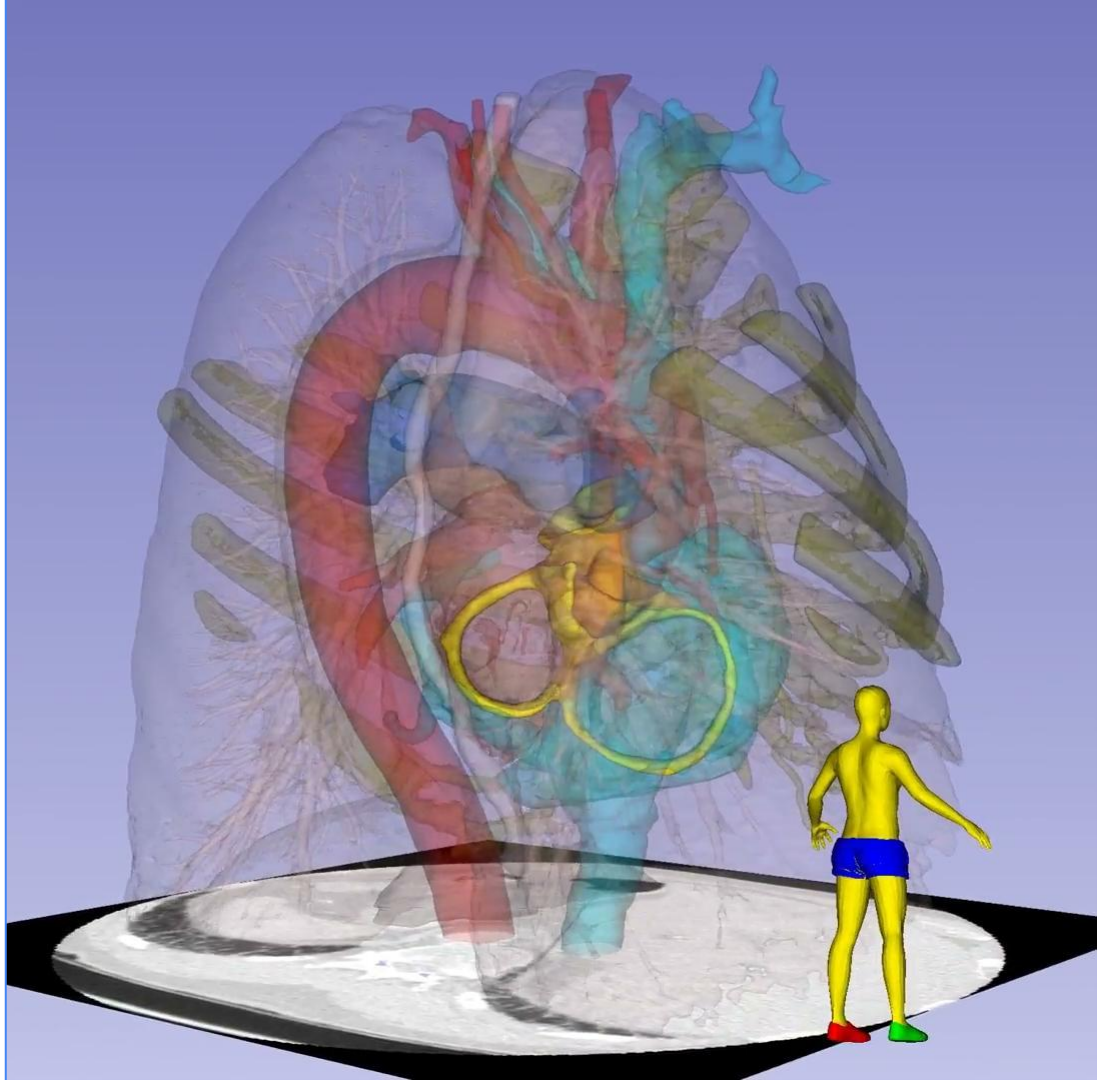
Blood volumes inside chambers & vessels *(walls removed)*

Little man & CT Slice for orientation

Normal anatomy

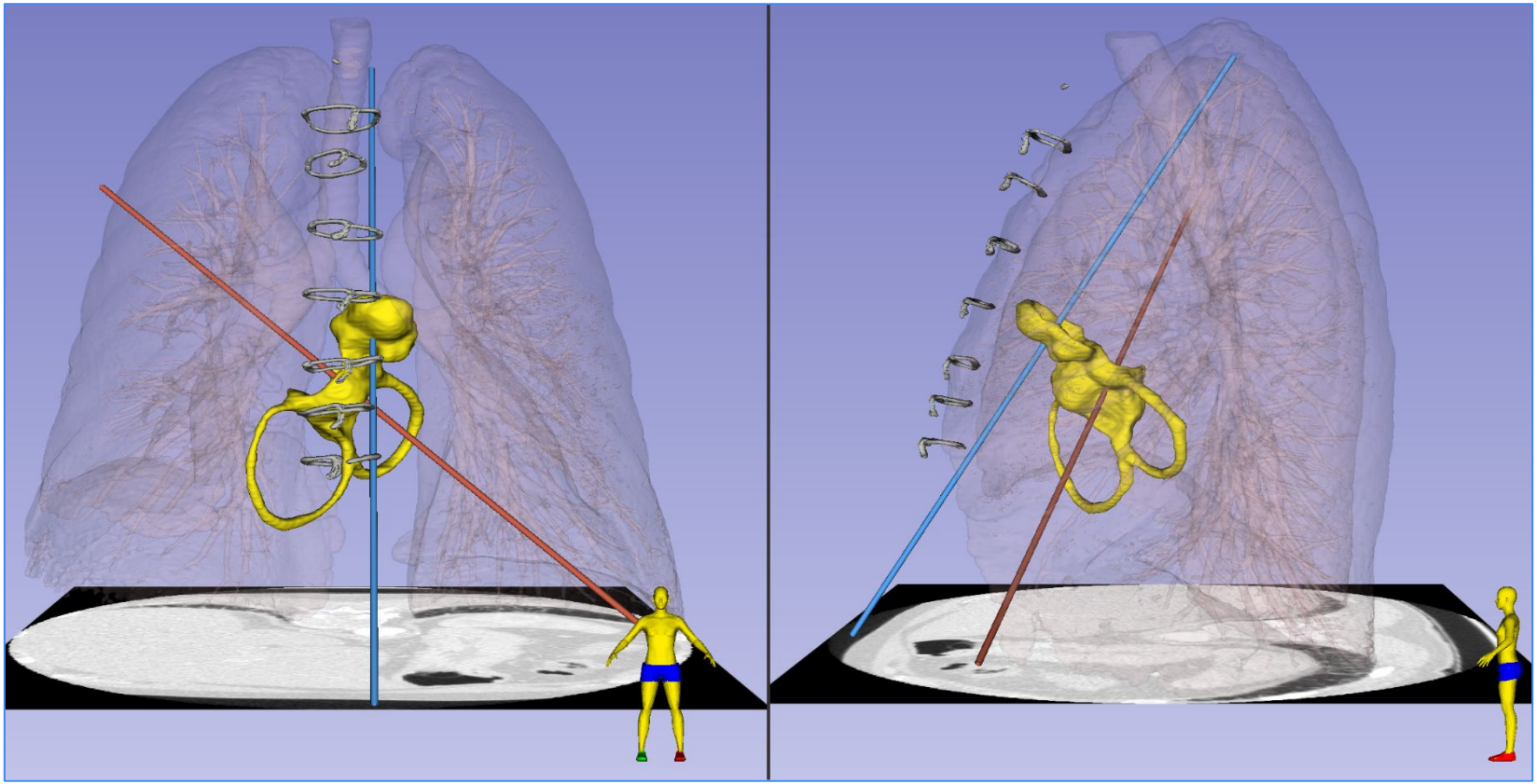
Pt. History of Aorto-Coronary Bypass (ACB/CABG)

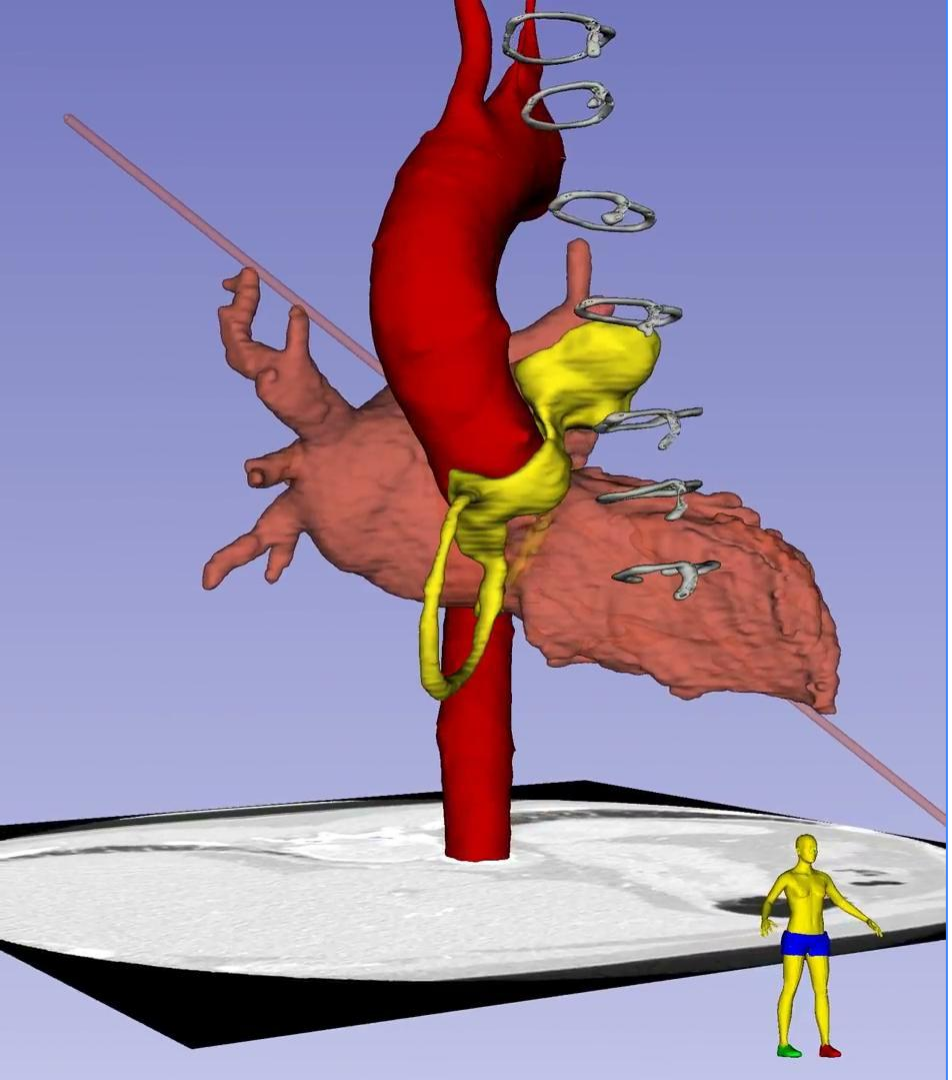
- Vein grafts coming off the ascending aorta
- Mobilized LIMA to LAD
- Sternal Wires

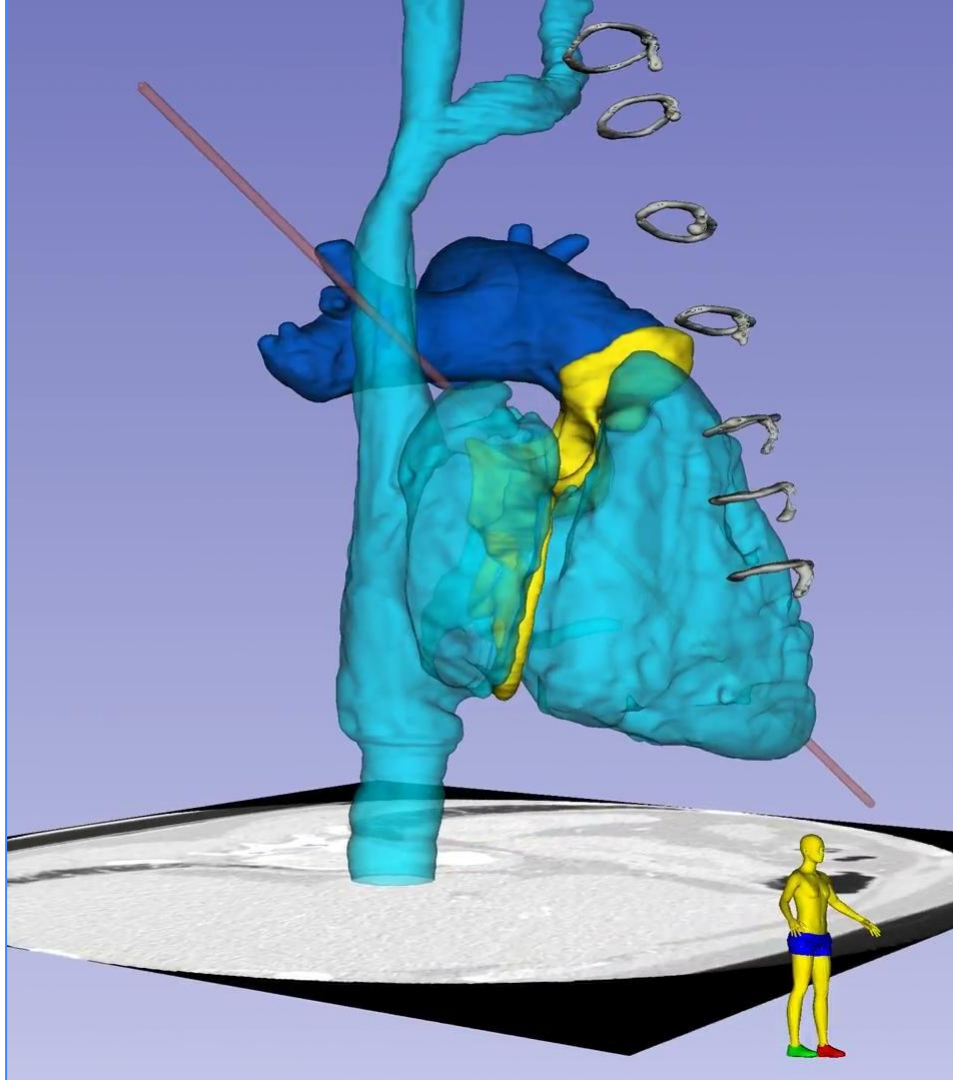


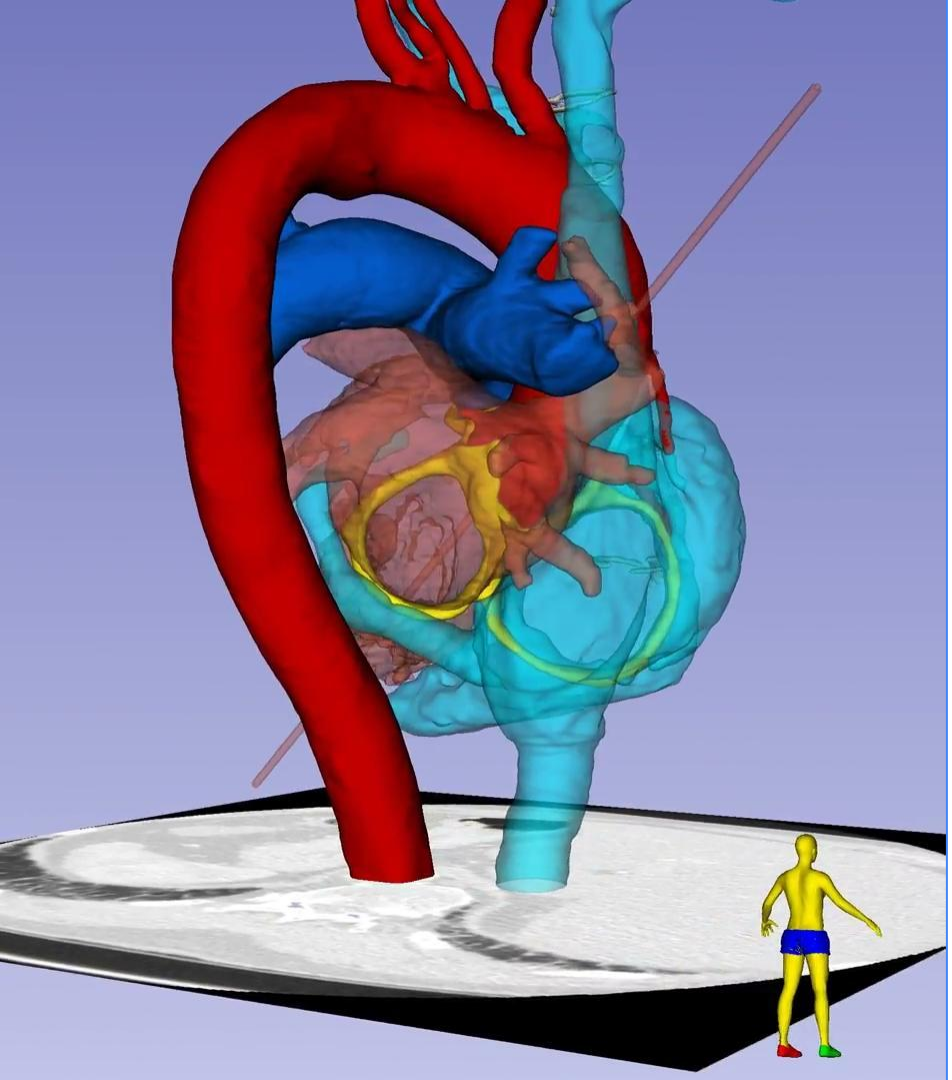
3DSlicer

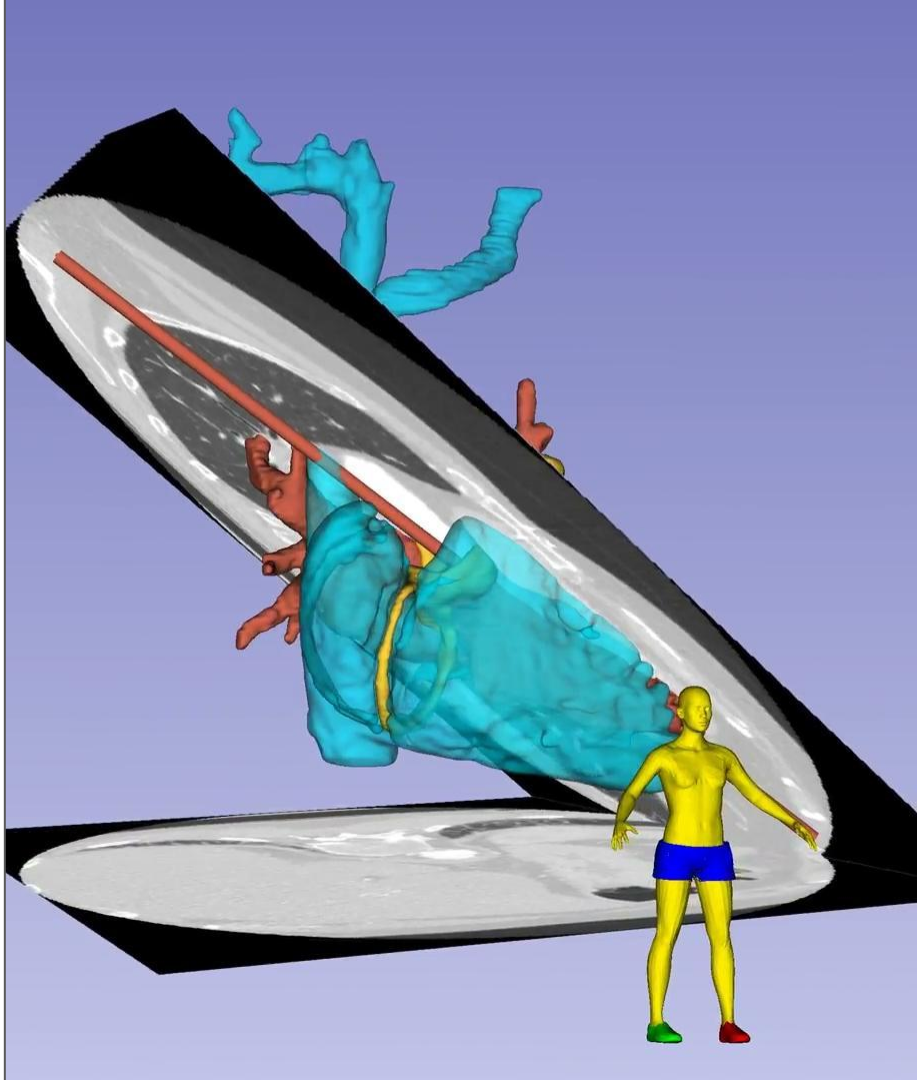
Heart Base: 3D Morphology











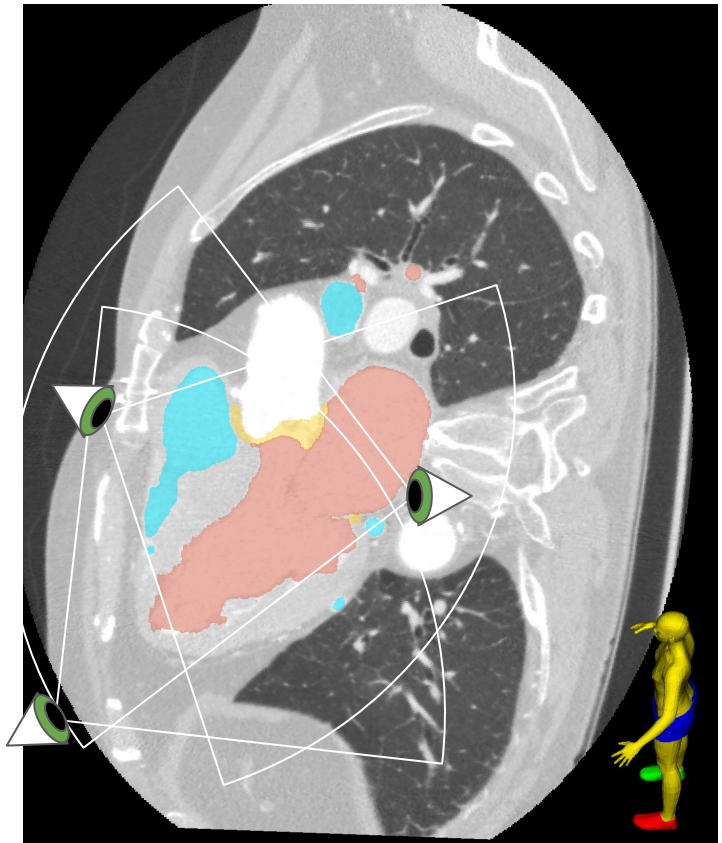
Cut-planes | Windows | Views

A cut-plane is the unique tomographic plane that includes **3 landmark points**.
e.g. **LV Long-Axis** cut-plane:

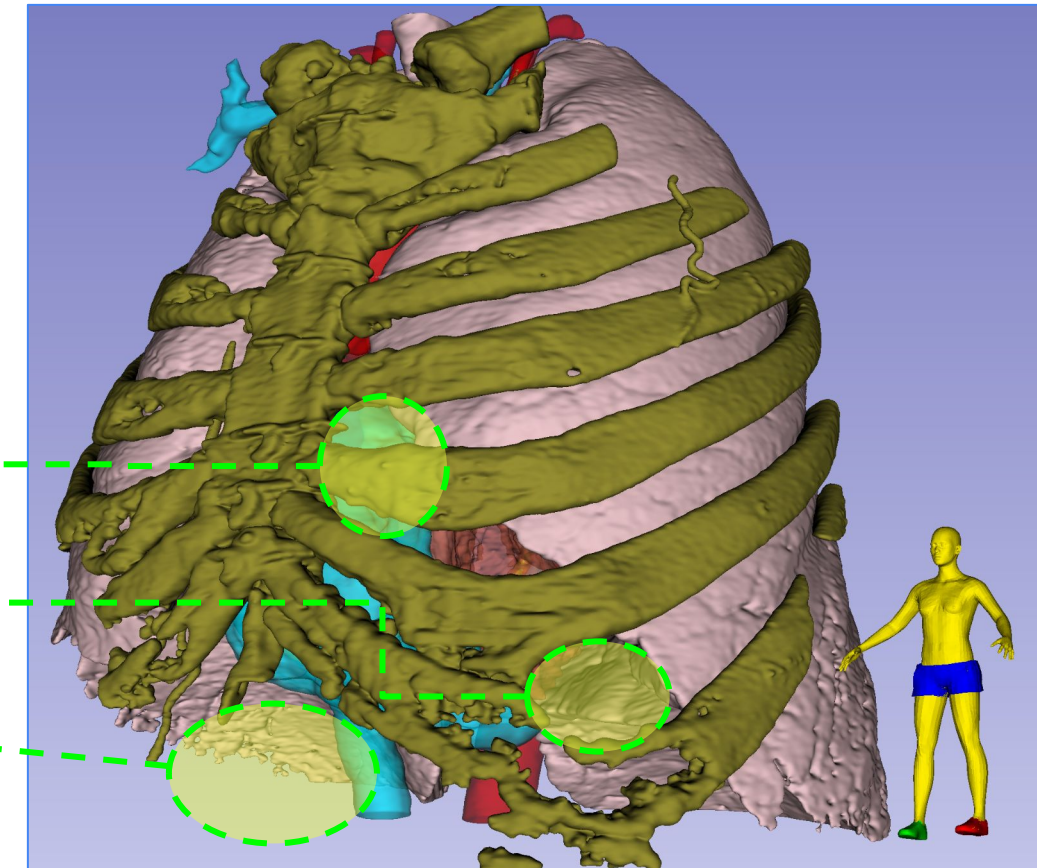
1. Aortic Valve Center
2. Mitral Valve Center
3. LV Apex

Views of LAX cut-plane from different **Windows:**

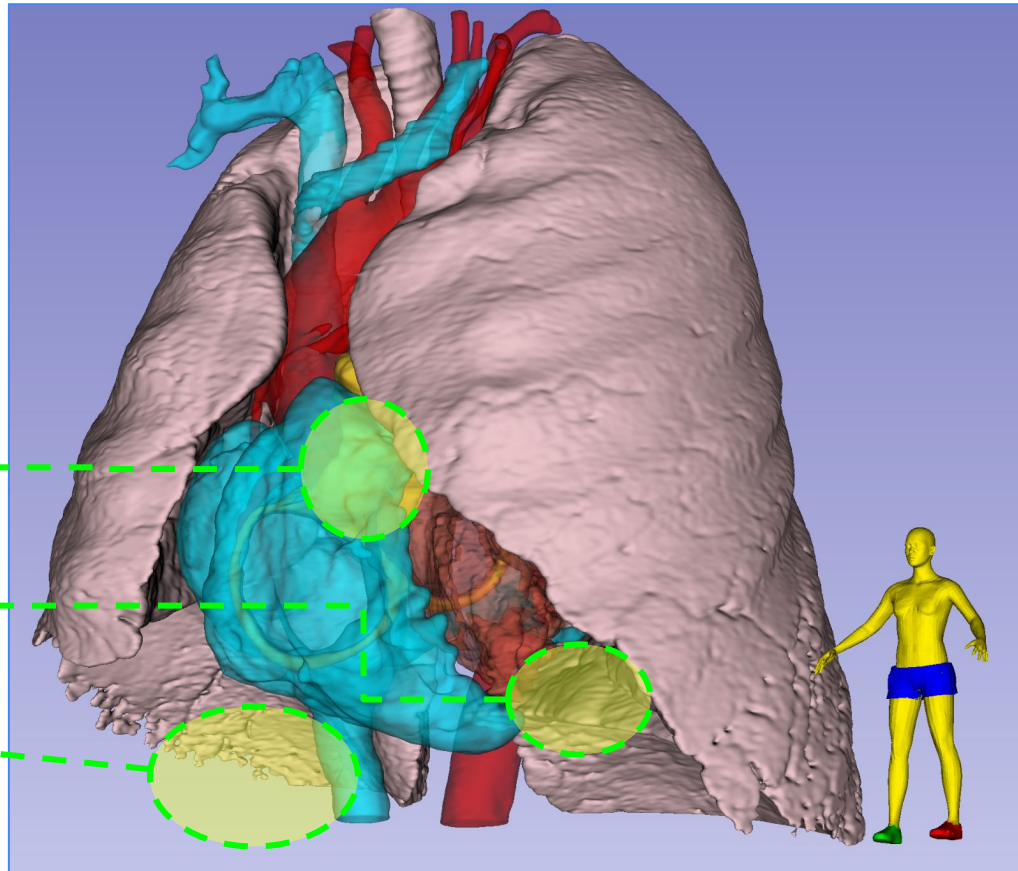
- Parasternal (TTE) window
  - Parasternal LAX
  - Parasternal AV LAX (zoom view of PLAX)
- Apical (TTE) window
  - Apical LAX
- Mid-Esophageal (TEE) window
  - Mid-esophageal LAX



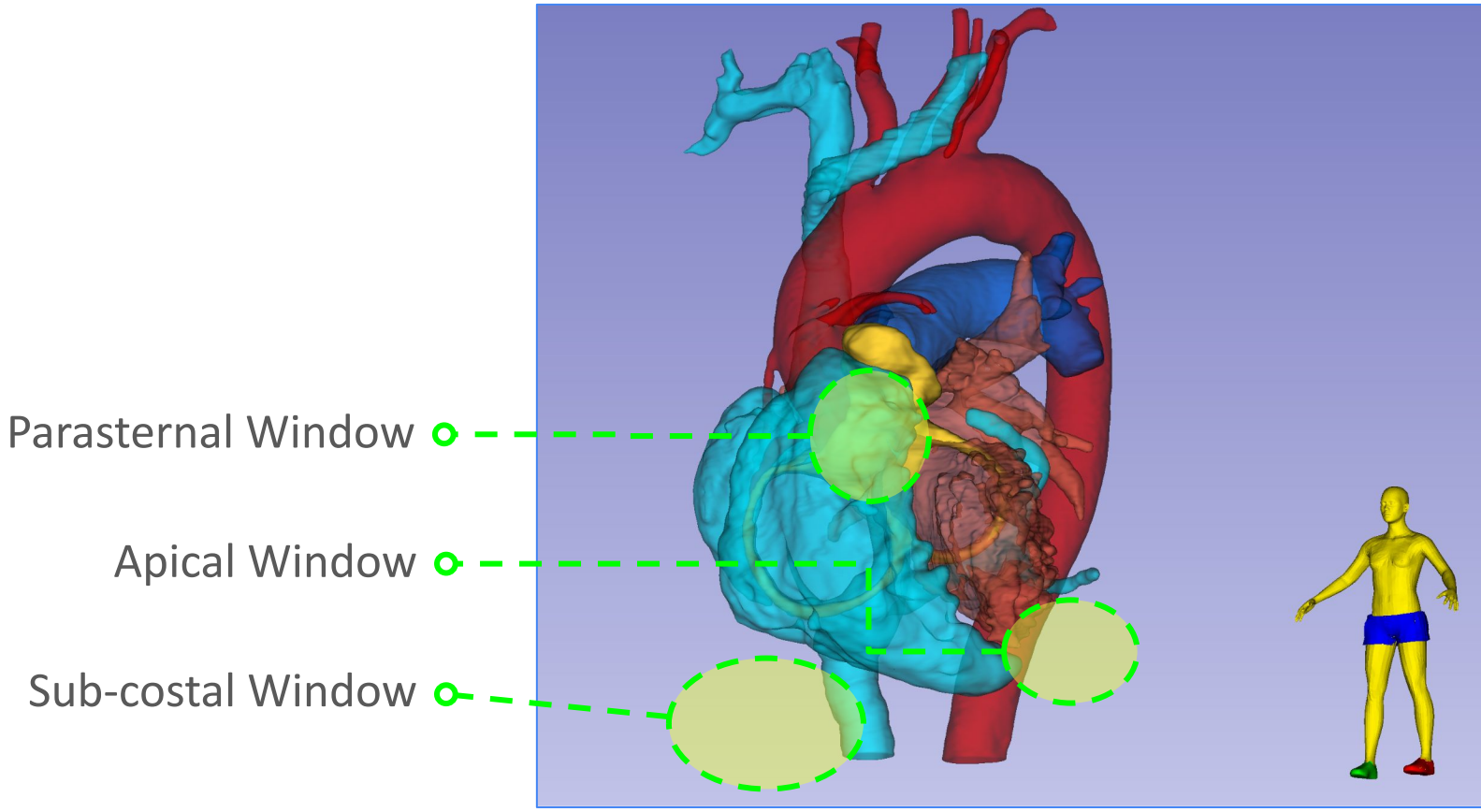
Chest Wall - Bone - Lung = TTE Windows



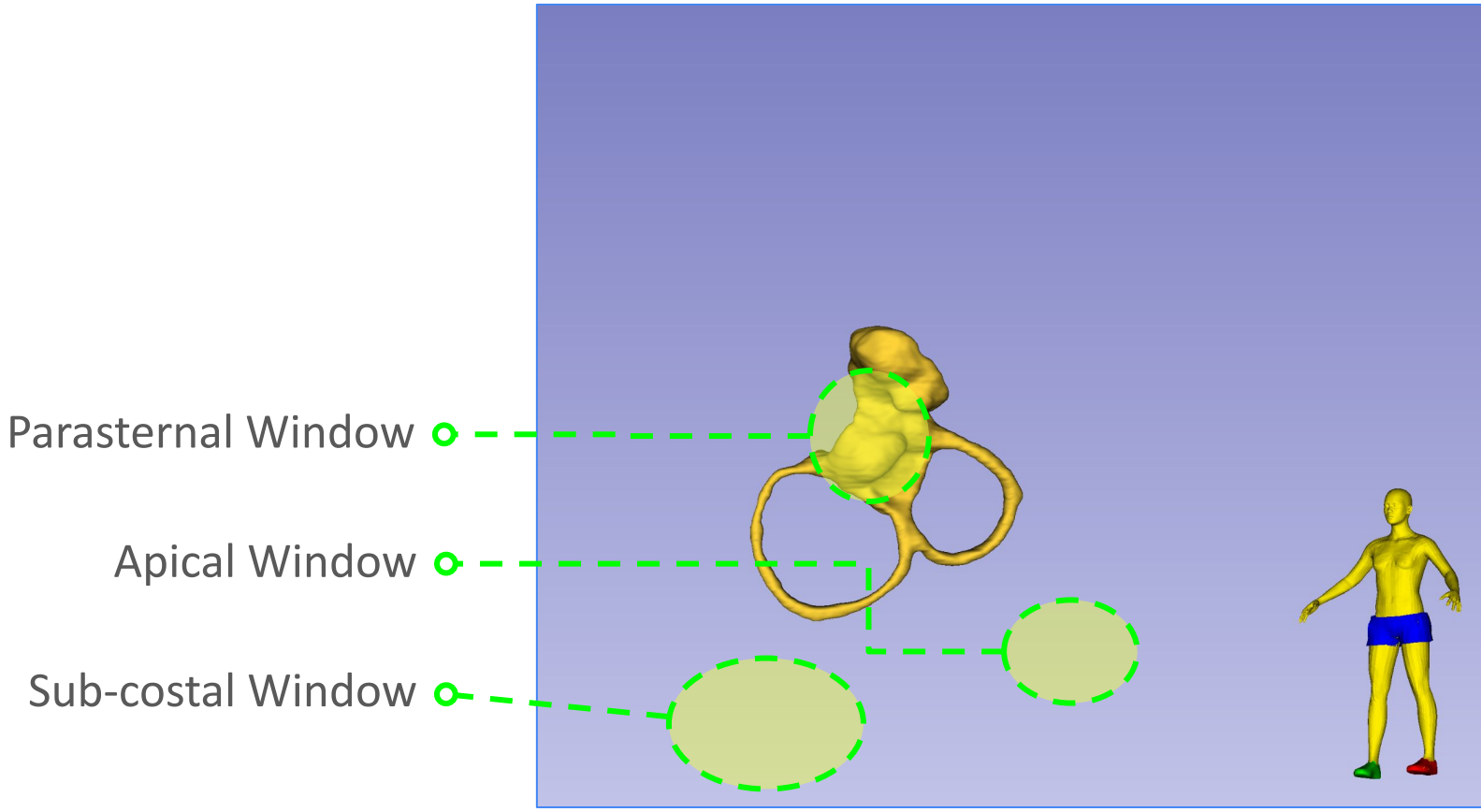
Chest wall - Bone - Lung = TTE Windows



Chest wall - Bone - Lung = **TTE Windows**



Chest wall - Bone - Lung = **TTE Windows**



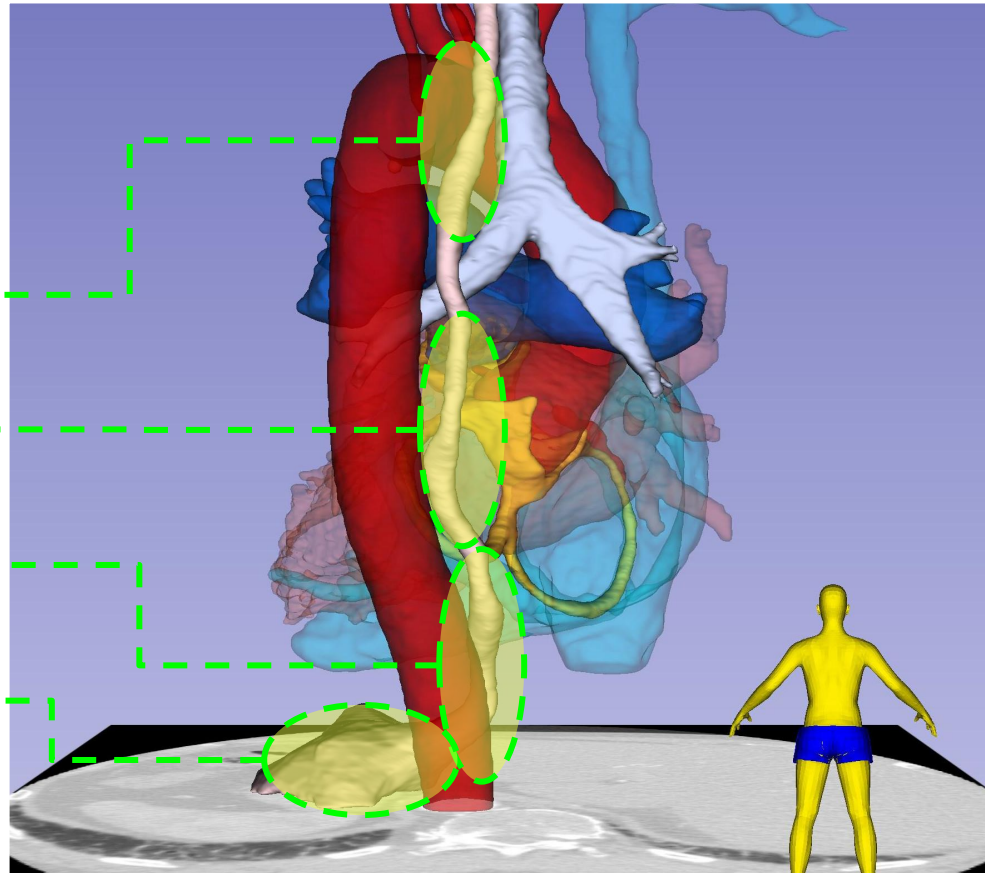
Esophagus - Airway = **TEE Windows**

Upper Esophageal (UE) Window

Mid-Esophageal (ME) Window

Lower Esophageal (LE) Window

Trans-gastric (TG) Window



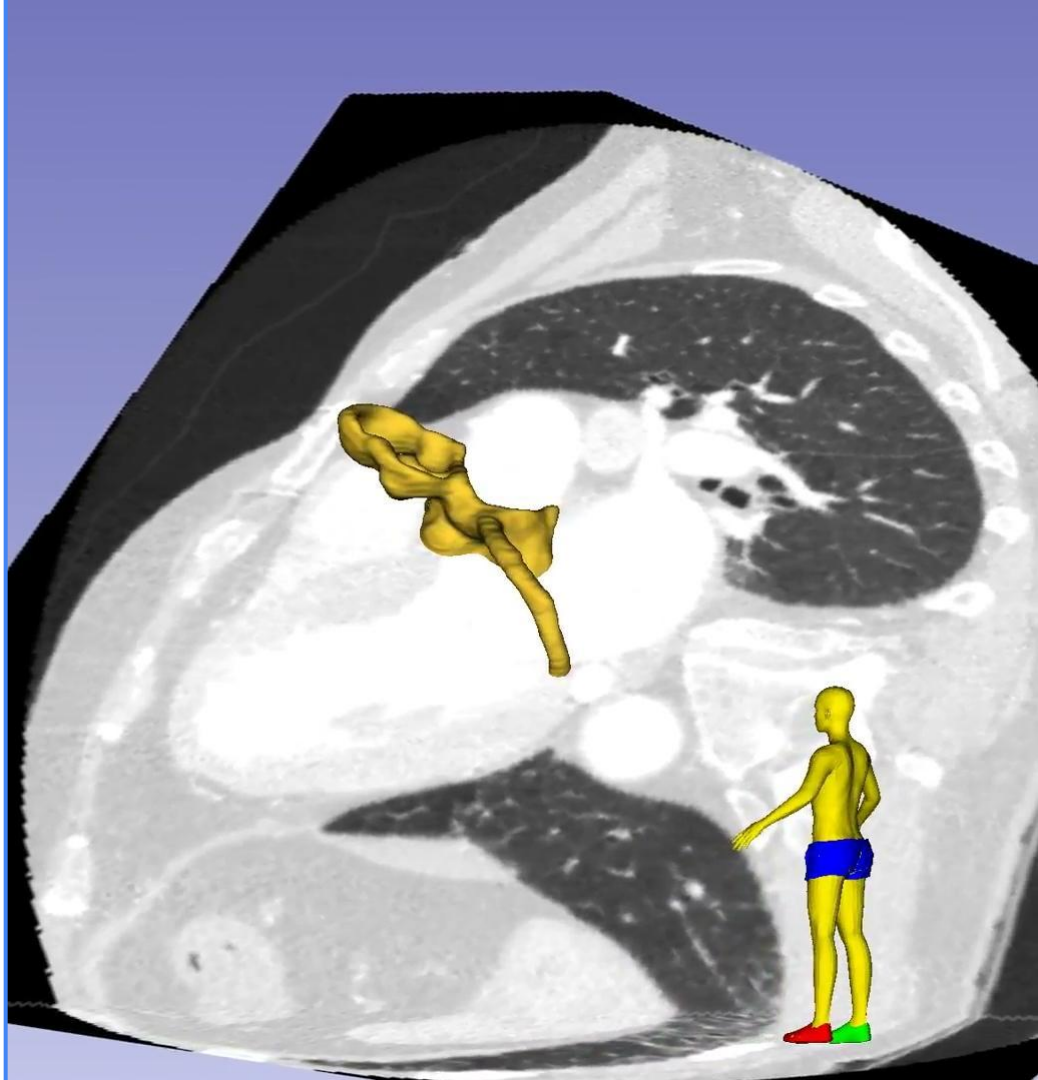
LV Long-Axis Cut-Plane

Landmarks

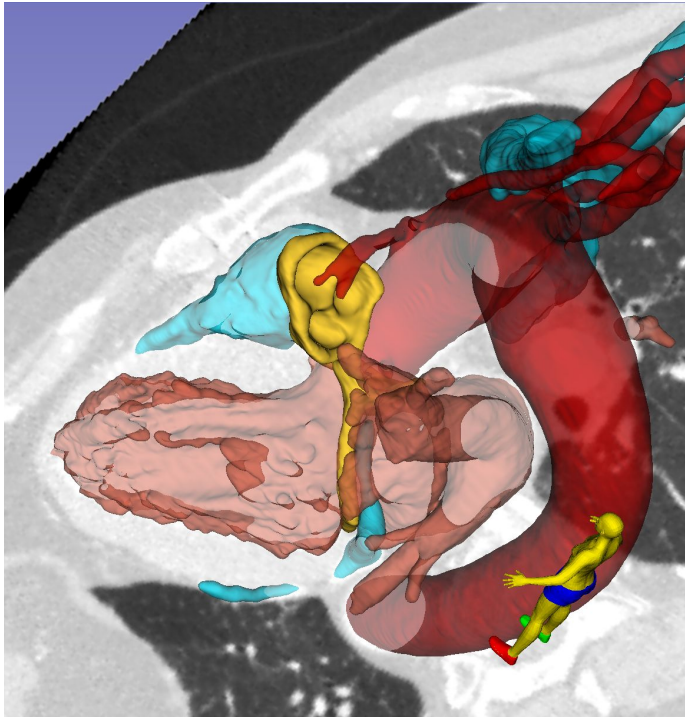
1. Center of AV
2. Center of MV
3. Apex

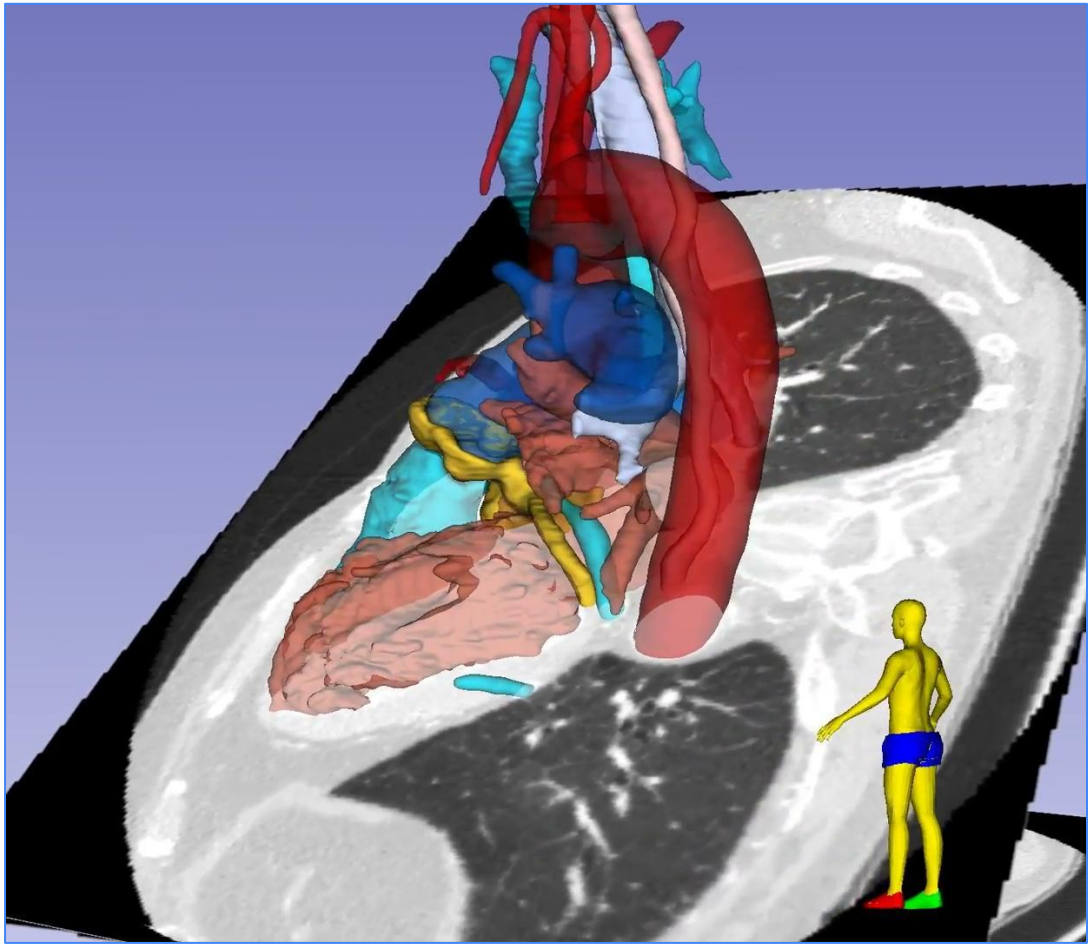
Views

- **Parasternal** LAX
- **Apical** LAX (3-chamber)
- ME LAX
- ME Aortic Valve LAX



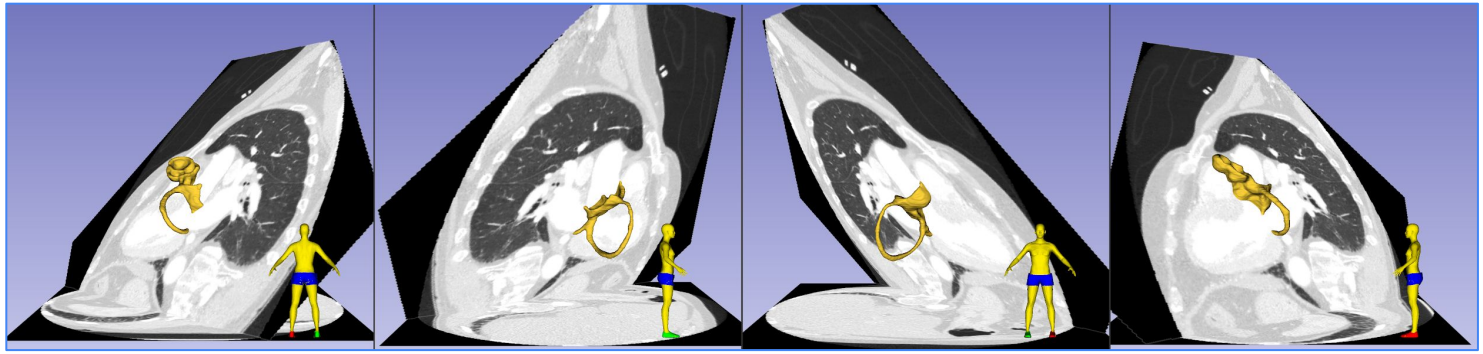
LV Long-Axis Cut-Plane

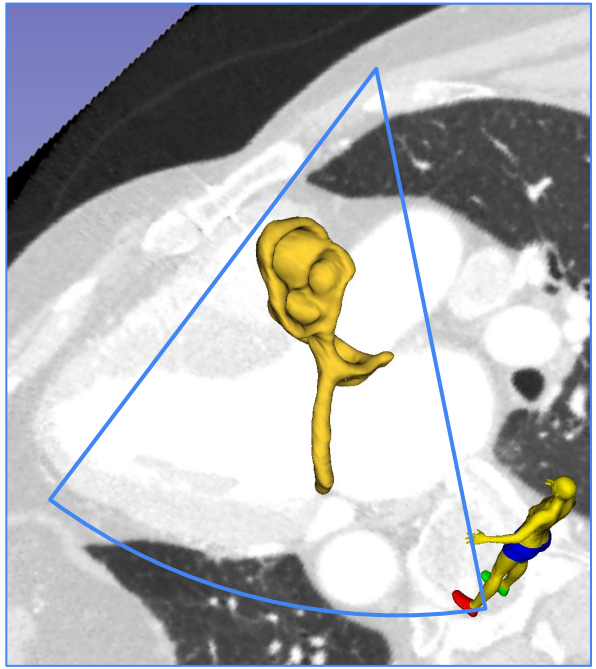


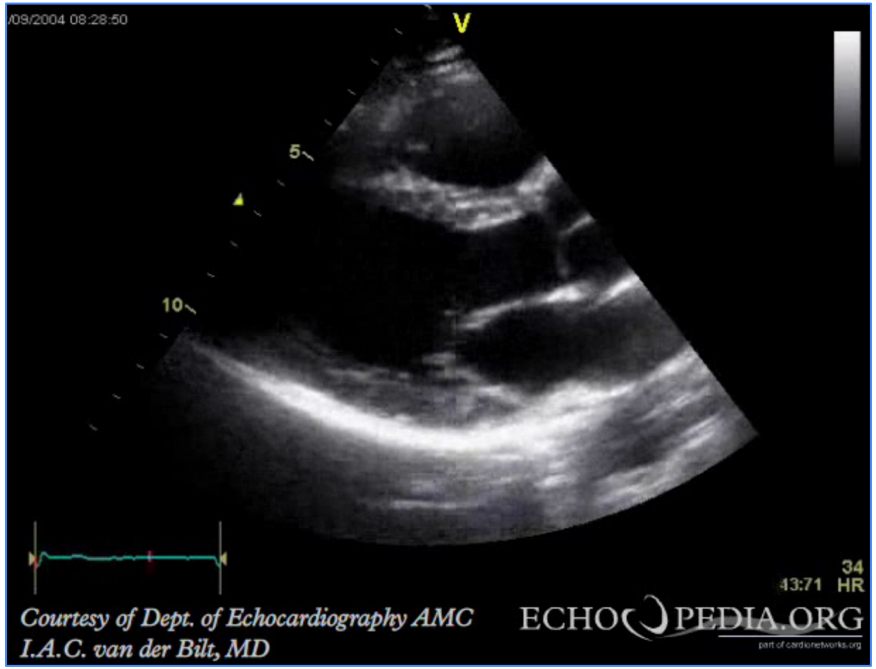


PSLAX view

(of LV LAX cut-plain)







3D Printed Modular Hearts & Base

Modular blood-pool models

For Anatomy training

Scale 50,100,200 %

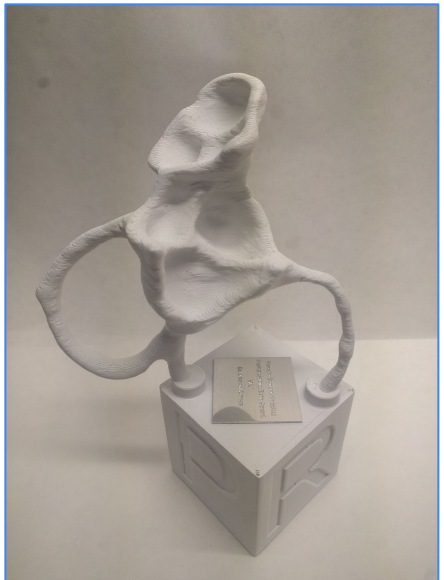
Patient-specific

Source: Cardiac CT

Segmentation: ITK-SNAP, 3D Slicer

Post-processing: Meshmixer, Blender

Print: Prusa MK3S + Polylite, PLA



Heart Atlas

35 Models to-date (De-identified, patient-based models collected with patient consent)

- ACHD
- Normal morphology
- Aortic root
- Heart Base

Open-source (cc-by 4.0 Int).

Printed models sold to fund project.

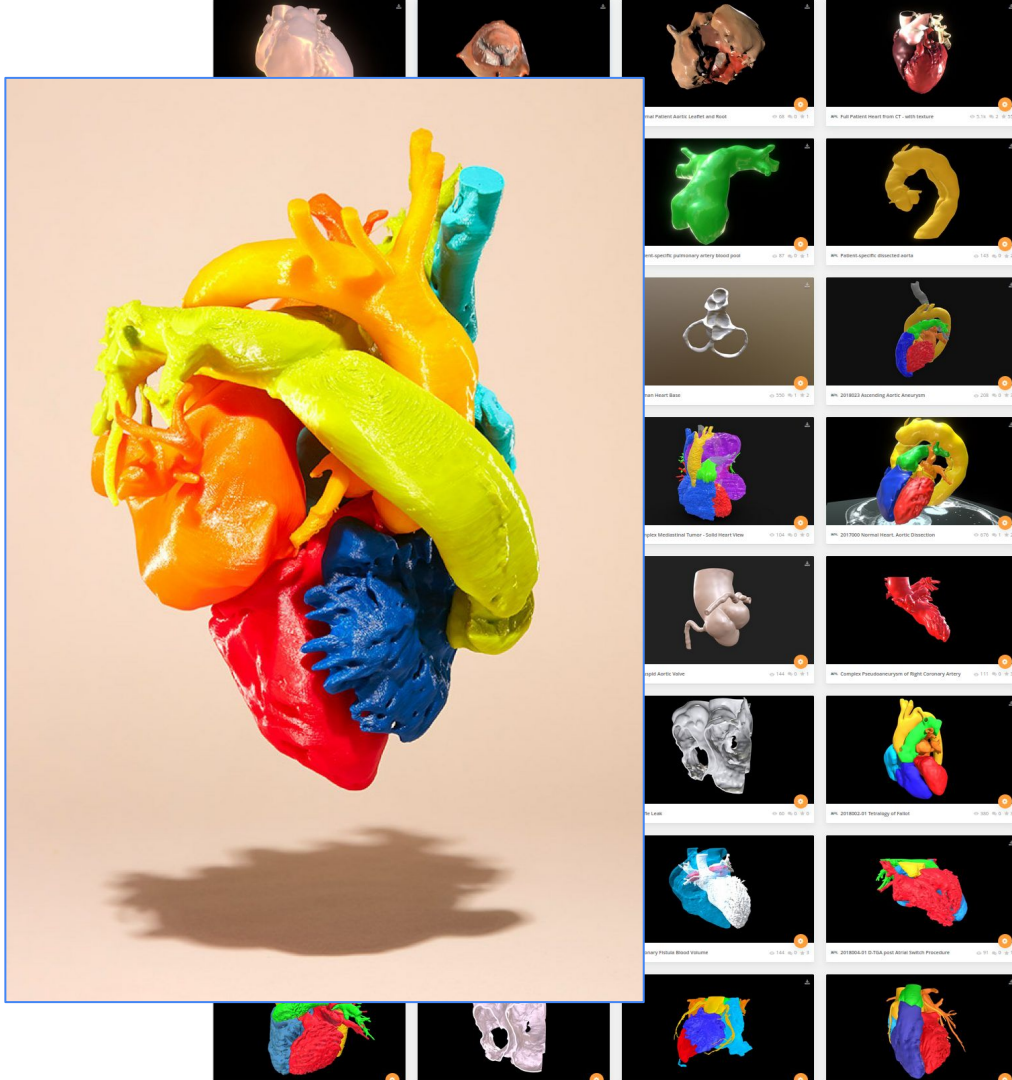
Free download: https://github.com/tgh-apil/TorontoHeartAtlas

3D gallery in development:

V1: https://apil.ca/toronto-3d-heart-atlas

V2: https://apil-experiments.web.app/#/3dviewer/viewer

Plan to link with NIH Heart Library



3DP Educational Models - Evidence/Gaps

Small studies showing high user satisfaction, some benefits in immediate comprehension compared to traditional methods.

> Kirkpatrick Levels 1-2, reaction & learning. Logistical and funding challenges for higher level evaluation

No systematic exploration of 2D/3D visualization/interaction modes for different types of learning.

> e.g. VR/AR vs On-screen rendering vs 3DP for anatomy teaching

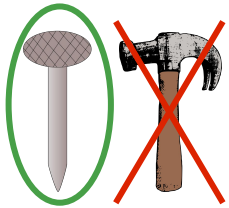
No established best-practices for phantom-based procedural teaching curricula

Su et al. Three-dimensional printing models in congenital heart disease education for medical students: a controlled comparative study. BMC Med Educ. 2018;18: 178. doi:10.1186/s12909-018-1293-0

Hojo et al. Utility of a Three-Dimensional Printed Pelvic Model for Lateral Pelvic Lymph Node Dissection Education: A Randomized Controlled Trial. J Am Coll Surg. 2019;229: 552-559.e3. doi:10.1016/j.jamcollsurg.2019.08.1443

Chytas et al. Three-dimensional printing in anatomy teaching: current evidence. Surg Radiol Anat. 2020;42: 835–841. doi:10.1007/s00276-020-02470-2

Procedural Training Phantoms: Development Approach



Develop phantoms as part of a need-driven curriculum

Identify task elements and corresponding learning objectives

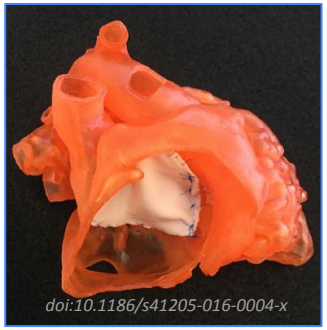
> Set-Up; Positioning; Landmarking; Ultrasound; Eye-Hand-Needle Coordination; Tactile Feedback

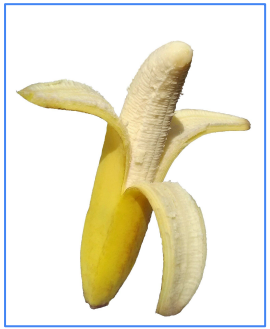
Identify learning stages and organize objectives by stage

Identify type (tactile, visual, ultrasound) & optimal level of fidelity required for each stage

Identify required interactions & corresponding modalities for each stage: 3D print / Render / VR / AR / Banana / Chicken

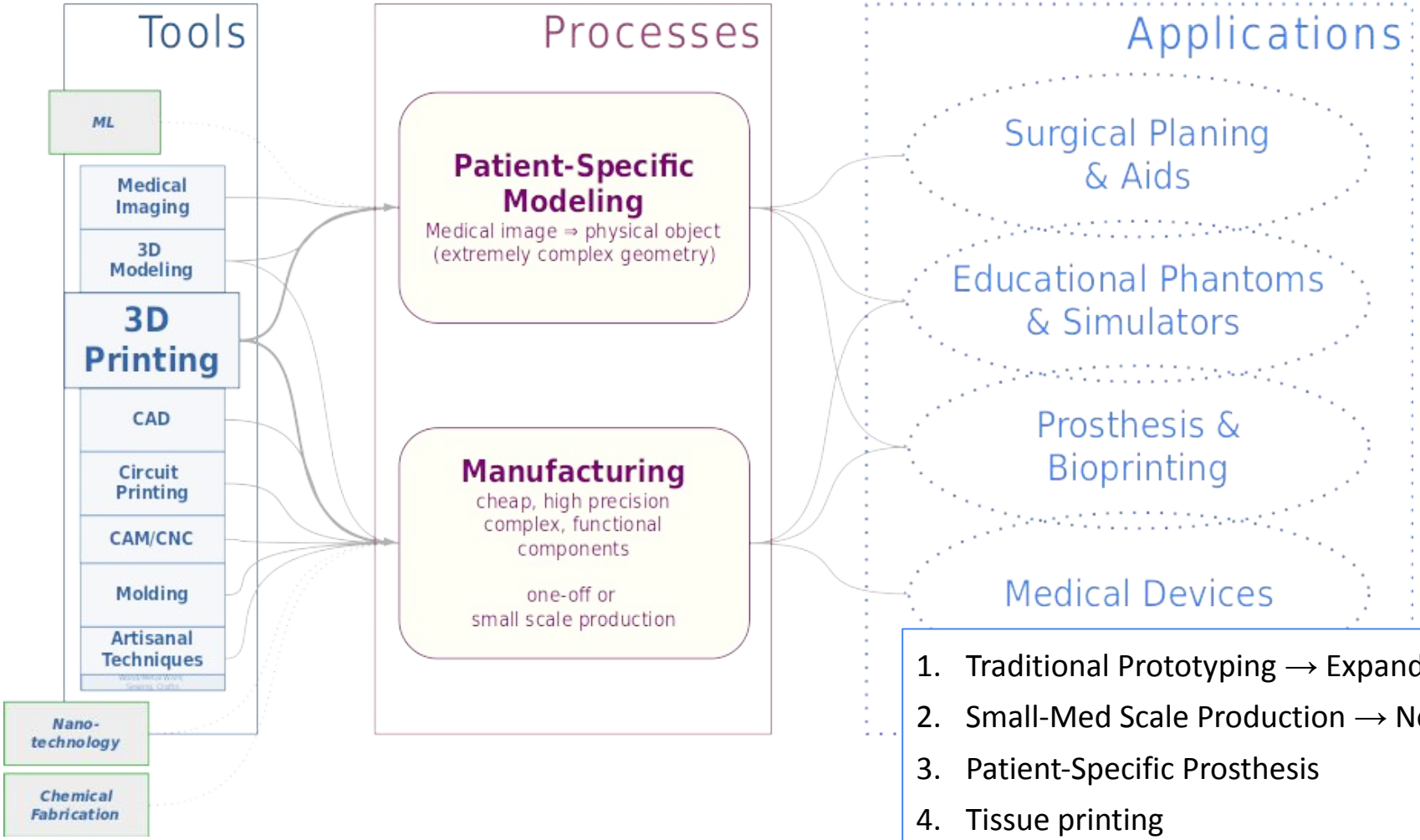
> Cost, Accessibility, Usability, Interactions, Storage





Banana by Filo gèn' cc-by-sa; Chicken by Marco Verch cc-by 2.0

Manufacturing



1. Traditional Prototyping ⟶ Expanded
2. Small-Med Scale Production ⟶ New
3. Patient-Specific Prosthesis
4. Tissue printing

Industrial Additive Manufacturing - Industrial Printers

https://www.forbes.com/sites/jenniferhicks/2016/03/22/fda-approved-3d-printed-drug-available-in-the-us/?sh=575f165b666b

https://3dprintingindustry.com/news/medical-giant-stryker-to-build-metal-3d-printing-facility-65623/

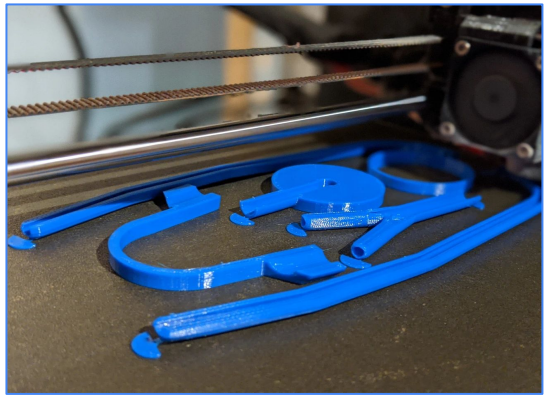
https://3dwithus.com/3d-printing-in-medicine

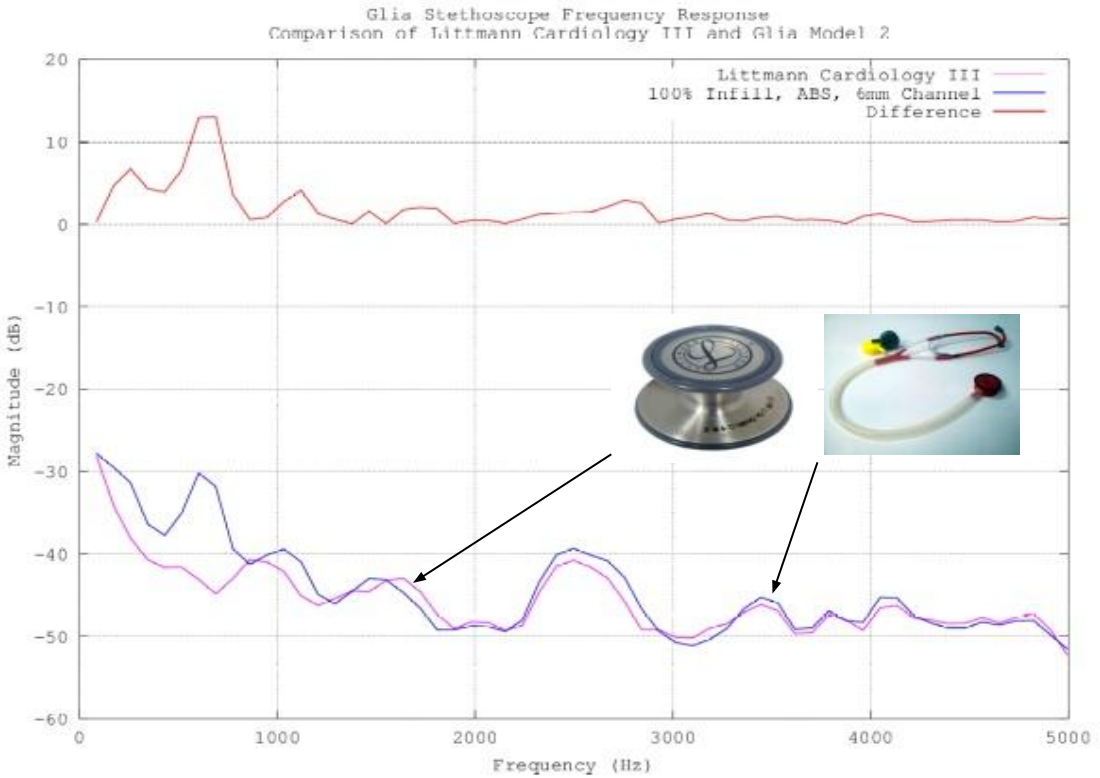
3D Printed Stethoscope (Glia) OS repository: https://github.com/GliaX/Stethoscope

glia
equal care

open software

open hardware





Pavlosky et al. Validation of an effective, low cost, Free/open access 3D-printed stethoscope. PLoS ONE. 2018;13: e0193087. doi:10.1371/journal.pone.0193087

Local Manufacturing - Desktop Printers

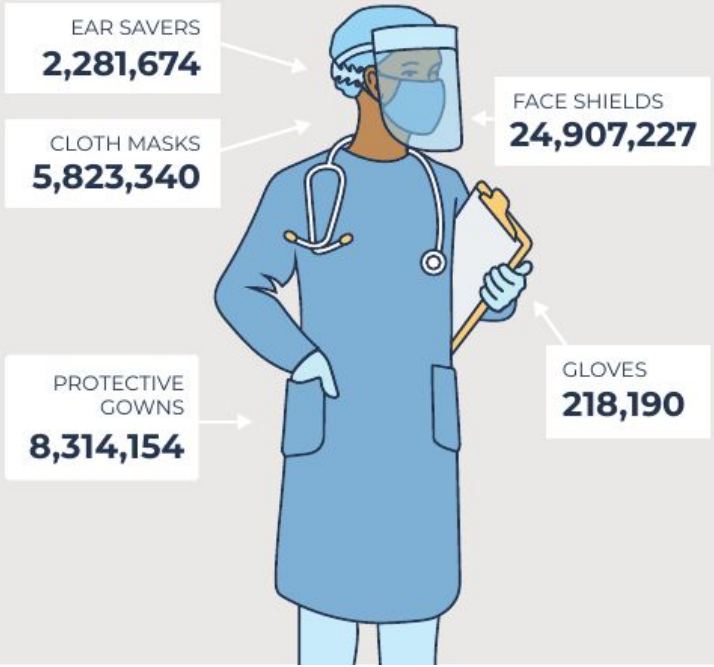
Created hundreds of new open source designs for medical supplies

200+ DESIGNS

available in the OSMS Library for **35 categories of PPE & supplies**

6,000% increase in unique visitors to the NIH 3D Print Exchange within 24 hours of engaging the maker community

Numerous medical inventions



Manufactured & delivered

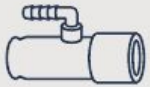
OVER 48 MILLION pieces of PPE and medical supplies

worth $271 million

including critical items such as:

NASAL SWABS
45,000

PAPR HOODS
59,289



VENTILATOR PORTS
4,021

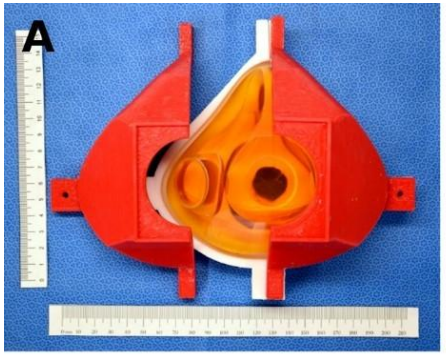
https://OSMS.li/impact

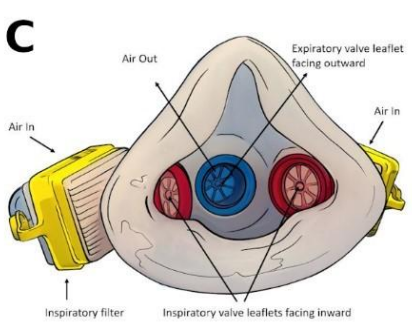
Stop-gap Silicone Respirator Mask (William Ng, TGH APIL)

Goal: Develop a locally manufacturable, reusable respirator meeting or exceeding N95 protection

Progress:

- Second generation design. Exceeds N95 filtration performance. Validated in 40 HCW.
- Undergoing testing and refinement to meet technical standards for resistance and CO_2 retention.
- Planned application for HC Emergency Use.



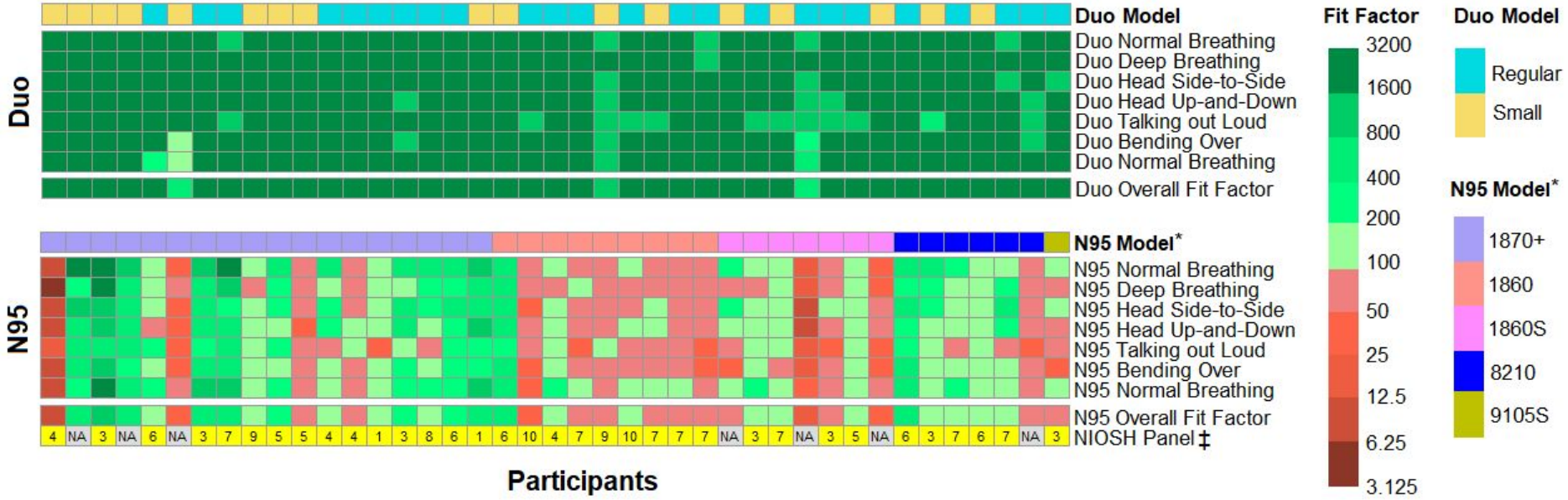


References:

1. https://github.com/tgh-apil/Reusable-N95-Respirator
2. Ng et al. PLoS ONE. 2020; 15(11):e0242304.
3. Anwari et al. PLoS ONE. 2021;16(3):e0247575.
4. Version 2 MS in review

Stop-Gap Respirator (Duo) vs N95:

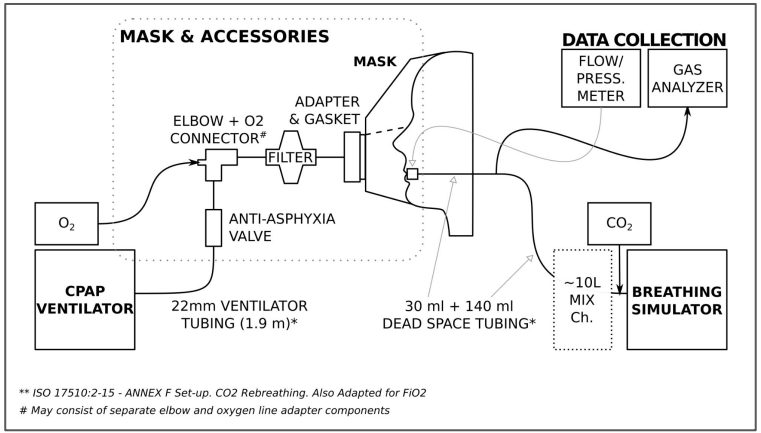
Quantitative Fit Testing in 40 HCW

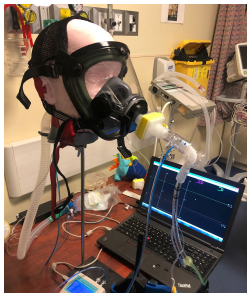


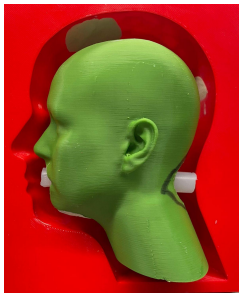
Overall **Pass Rate**:

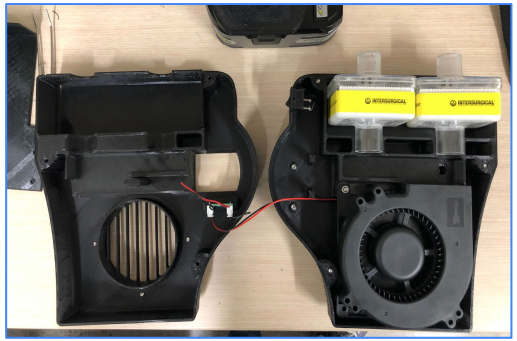
- **N95: 58.5%** (most failures in dynamic maneuvers; difference across models)
- **Reusable SGR: 100%**

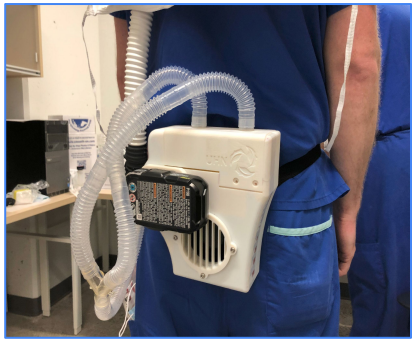
Hospital-based Emergency Manufacturing











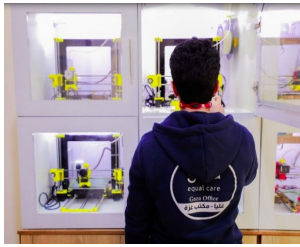
Clinkard et al. Evaluation of N95 respirators, modified snorkel masks and low-cost powered air-purifying respirators: a prospective observational cohort study in healthcare workers. Anaesthesia. 2021;76: 617–622. doi:10.1111/anae.15392

Locally Manufacturable Medical Devices

Devices in development

- Pulse Oximeter: Clinical Validation and regulatory application
- ECG: Clinical Validation and regulatory application
- Otoscope: Evaluation
- Dialysis components and adaptors
- Ultrasound, CT

Standards, best practice, Regulatory frameworks

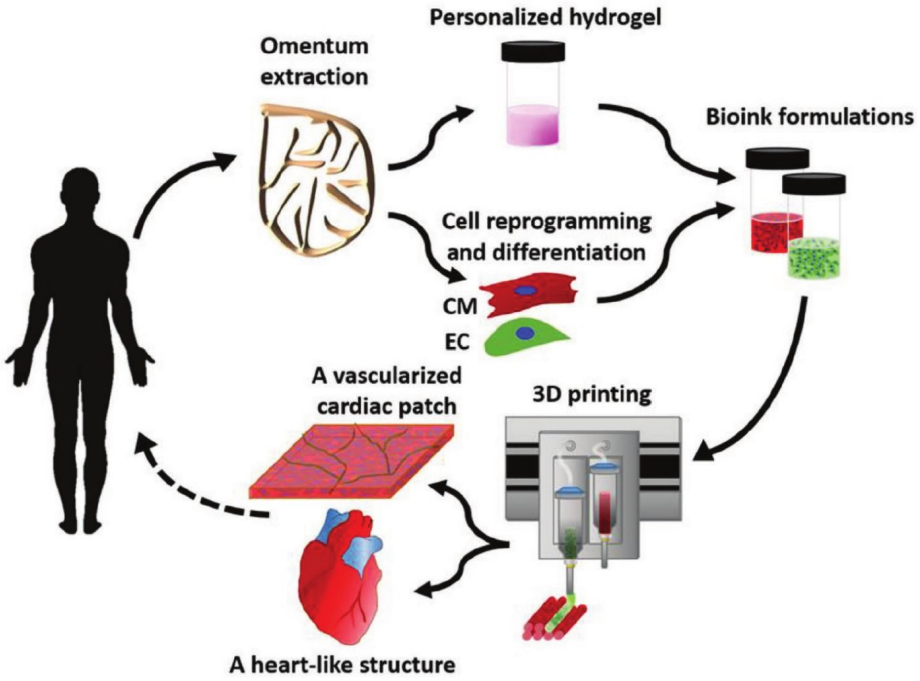


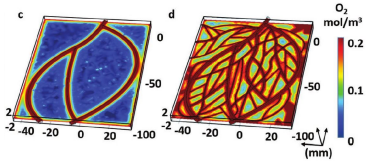
Why? Access, Customization, Resilience ...

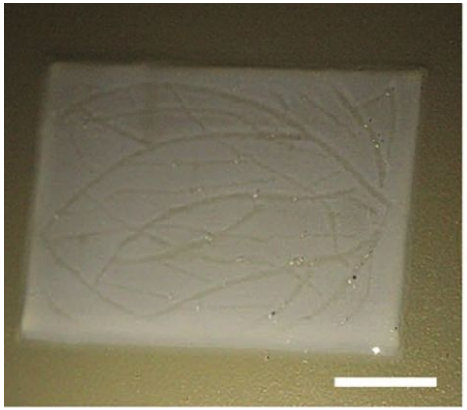
Emergency Preparedness for Supply Chain Disruption: open-source digital stockpile of essential devices

Merlo S. (2020) Building Medical Supply Chain Resilience through a U.S. Manufacturing Reserve and Digital Stockpile. Day One Project; https://www.dayoneproject.org/post/u-s-prototyping-manufacturing-reserve-u-s-digital-stockpile

Bioprinting







Noor N, Shapira A, Edri R, Gal I, Wertheim L, Dvir T. 3D Printing of Personalized Thick and Perfusable Cardiac Patches and Hearts. Advanced Science. 2019;6: 1900344. doi:10.1002/advs.201900344

The Costs

3D Printing in Medicine Future ...

Clinical Planning

Multi-modal visualization
Image fusion
3DP, AR/VR, Rendering
In-situ, intra-procedural visualization

Demonstration Education Models

Digital modalities will likely gain wider use due to range of interactions and ease of access if AR/VR hardware becomes more widespread

Industrial manufacturing

Curriculum-based procedural education

"The time for learning curves on patients has passed"

The time for force fittin curricula to the limits available devices is passing.

Locally manufacturable medical devices

Institutional support; regulatory progress

Bio-printing & Tissue engineering

Implantable tissue: skin grafts, functional patches, whole organs.

Role of 3DP specifically vs other TE methods?

Hope

Desktop 3D printing makes it possible for
almost anyone (with basic digital literacy and semi-reliable electricity)
to build complex, functional objects
of almost every imaginable shape
with high quality, at scale
with initial infrastructure costs similar to a new cell phone

---

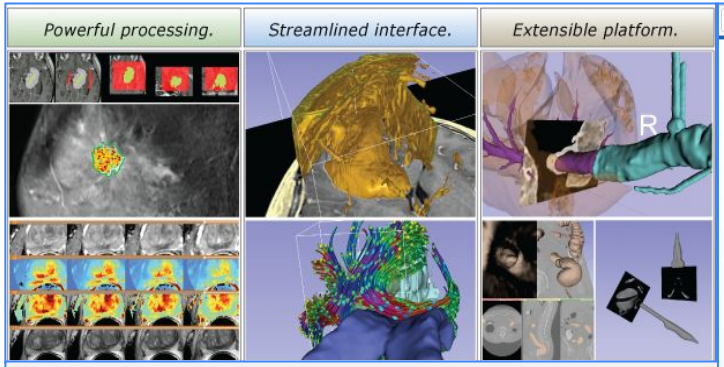
Lots of potential ...

But very little of has been translated into improving the care of the sick
(beyond isolated cases)

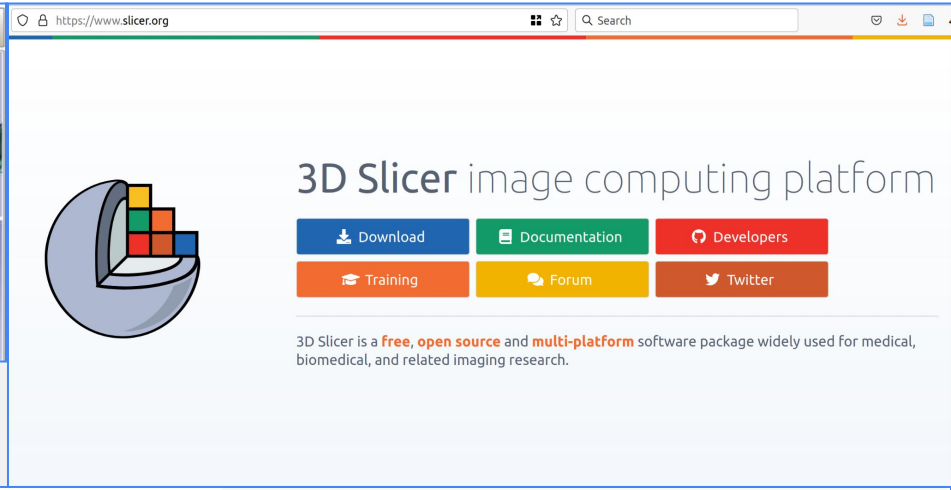
Much of the potential (& challenges & hazards) lie in the democratization of the technology
Not just in terms of ***Access*** but also of ***Technology Development***

open software

open hardware

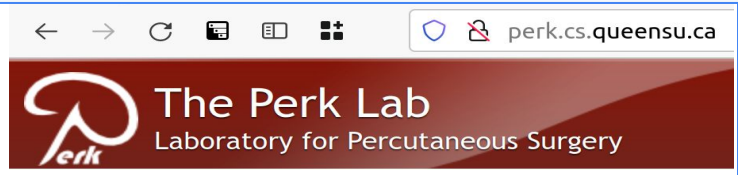


Brigham and Women's Hospital
Founding Member, Mass General Brigham



Educational VR Set-up & Workflow:
http://perk.cs.queensu.ca/sites/perkd7.cs.queensu.ca/files/Lasso2019.pdf

3D Slicer Annual Boot Camp: (Course content at link below)
https://github.com/PerkLab/PerkLabBootcamp/tree/bootcamp-2021



PICSL

PENN IMAGE COMPUTING & SCIENCE LAB

Acknowledgements

Lab: Alan Zalewski, V. Anwari, J. Fisher, J. Qua Hiansen, A. Mbadjeu Hondjeu, W. Ng, S. Russell, L. Fedorko

Collaborators and mentors: BID Valve Research Group (Prof. Mahmood et al.), K. Behdinan, D. Clinkard, D. Gucciardo, S. Plimmer, M. Xiao, T. Yan

UHN: Peter Munk Cardiac Center, Medical Engineering, JDMI, RT, OR, MDRD, Techna Institute, IPAC, Animal Lab
Interdepartmental Division of Critical Care Medicine

Glia Inc. UHN-SHS Anesthesia Associates, Thornhill Medical

glia
equal care

UHN FOUNDATION

The Lynn & Arnold Irwin
APIL Advanced Perioperative Imaging Lab

The Lynn & Arnold Irwin

APIL Advanced Perioperative Imaging Lab

azad.mashari@uhn.ca
apil.ca
@APIL_TGH