3D-Printing Patient-Specific Phantoms For Imaging and Radiation Dosimetry: Recent Progress, Challenges, and Future Directions

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NIH Collaborators

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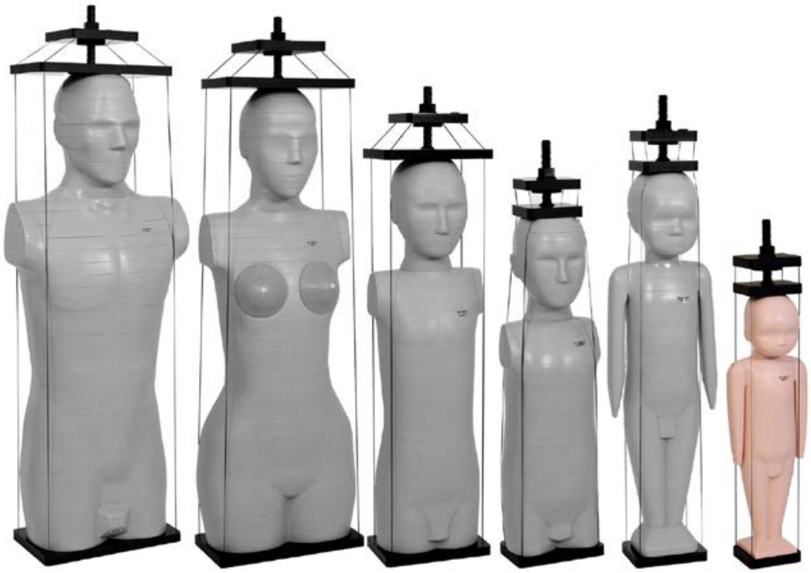
External Collaborators

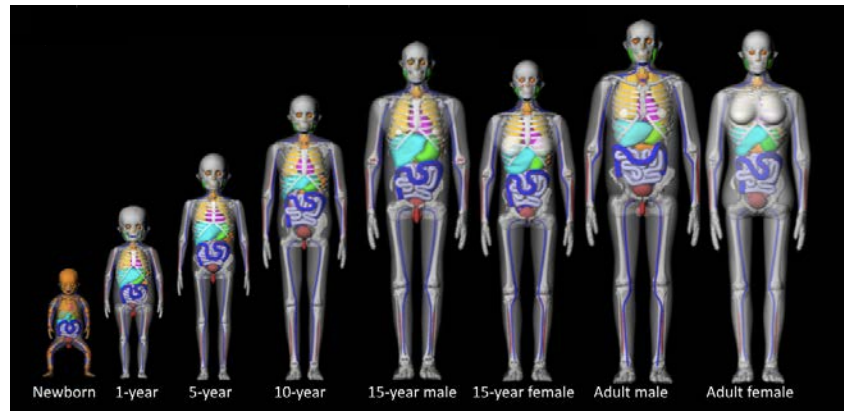
- Heather Chen-Mayer (NIST)
- Jerimy Polf (UMD)
- Tetyana Rudenko (MC)

Two Ways To Determine Patient Dose

Measurements



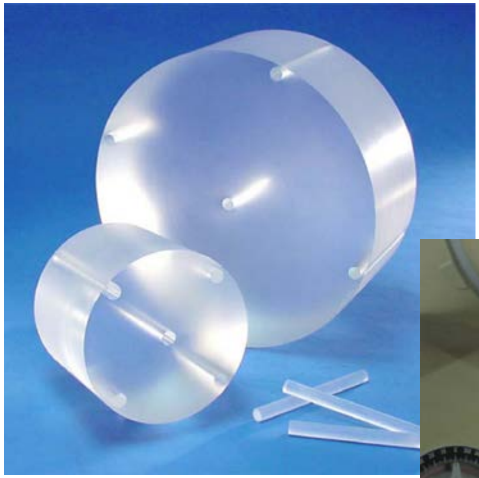
Calculations



Two Categories Of Physical Phantoms

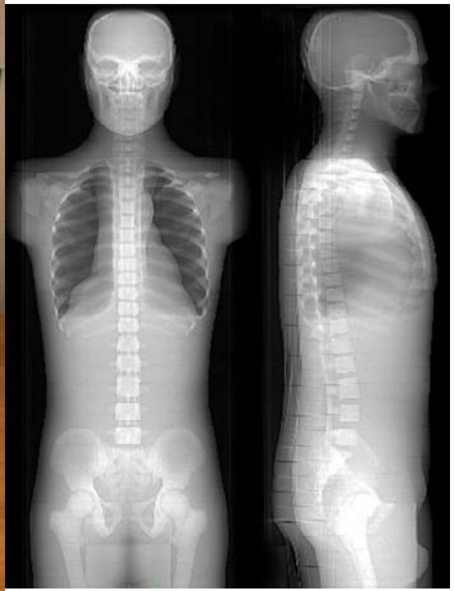
Anthropometric

- Simple, well-defined geometries
- Easy to reproduce and standardize
- Used for quality control, characterizing equipment



Anthropomorphic

- "Realistic" body/organ shapes
- Tissue equivalent materials
- Used as surrogate for human anatomy & organ dosimetry



Customized Anthropomorphic Phantoms Needed For Dose Verification

- Computational dosimetry must be benchmarked against experimental measurements
- Commercial phantoms are expensive, available only in limited variety, and have not changed for decades

Objective

To explore 3D-printing as a solution for on-demand fabrication of patient-specific phantoms

1) Direct fabrication of pediatric torso using thermoplastic extruder
2) 3D-printing a mold for casting a fat layer for simulating an obese patient

Known Challenges

Many groups have explored 3D-printing for this purpose and have consistently identified three barriers to progress

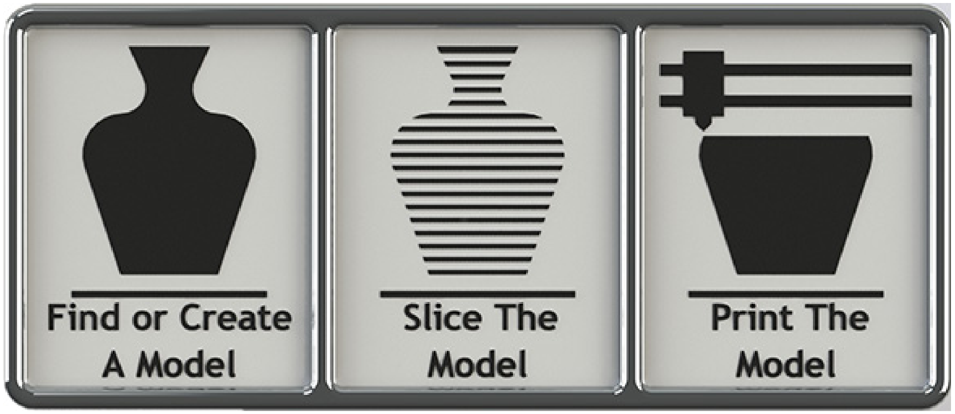
1) Limited variety of materials for simulating tissues with mass densities ranging from 0.25 g/cm^3 (lung) to 1.85 g/cm^3 (bone)
2) The need to print parts out of multiple materials simultaneously
3) Printer build size and speed limit the printing of life-size parts

To our knowledge there is no commercial 3D printer on the market today which can fully overcome <u>ALL</u> of these challenges

The 3D-Printing Process

A group of technologies in which parts are quickly produced from 3D data via additive fabrication

1) Create a computer-aid design (CAD) model of part
2) Convert model to triangulated surface mesh (STL)
3) Slice STL file into thin cross-sectional layers
4) Construct part one layer atop another
5) Clean and finish part

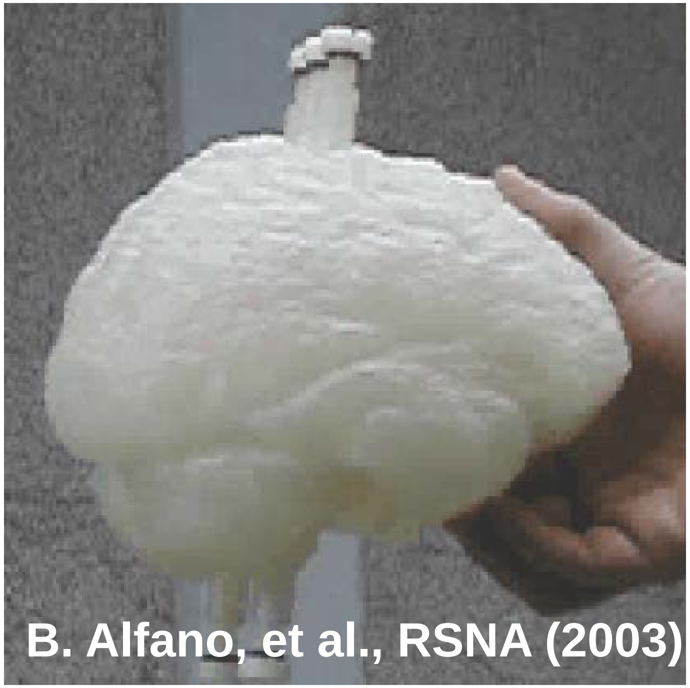


3D-Printing In Medicine

- Visualize medical problems
- Surgical/dental guides
- Medical device manufacturing (e.g. hearing aids)
- Investment casting patterns for prosthetic implants
- Imaging phantoms with fillable compartments

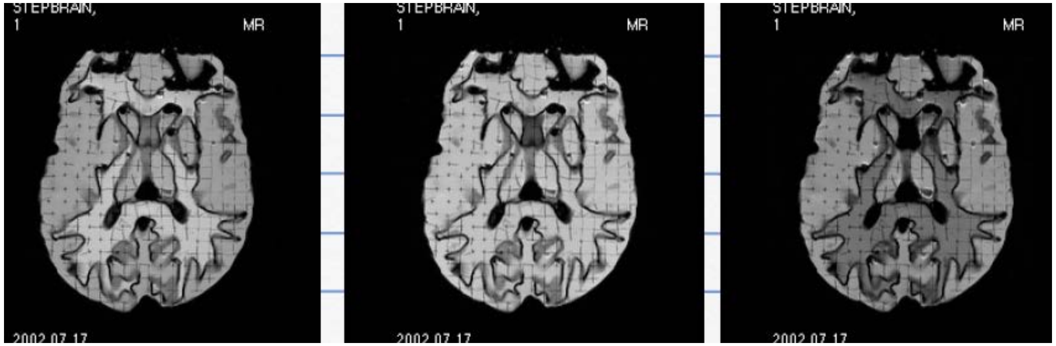
Stereolithography

STEP-BRAIN



B. Alfano, et al., RSNA (2003)

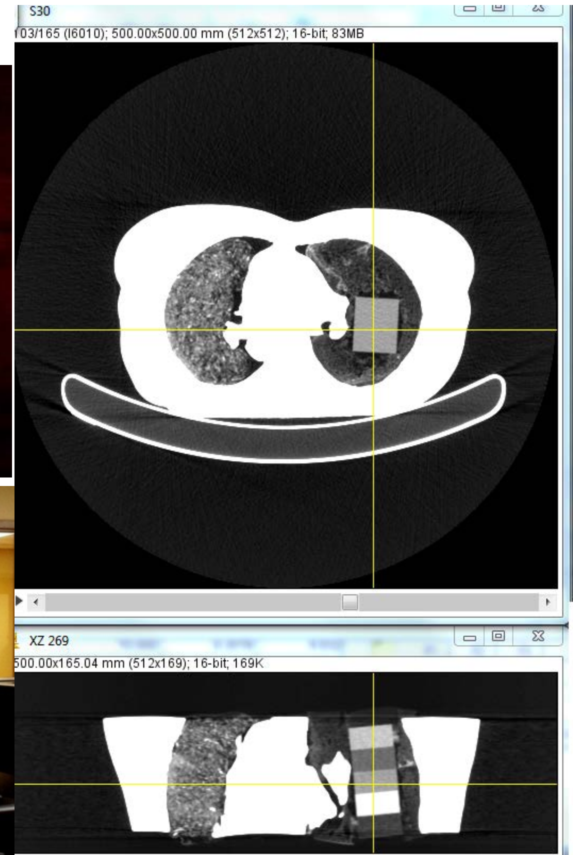
MRI

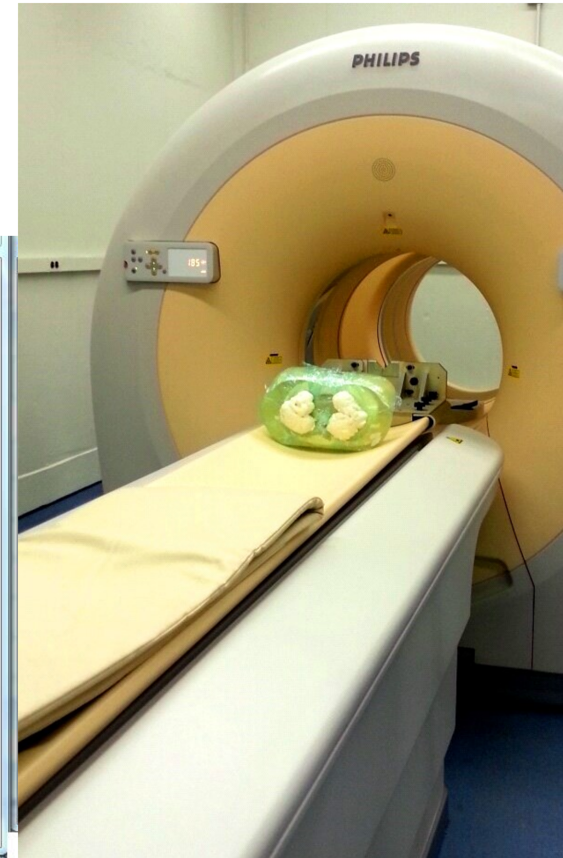


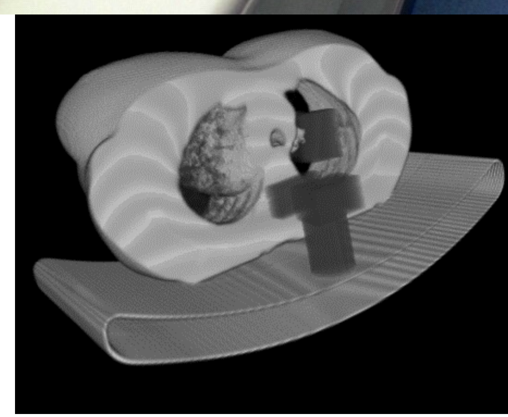
CT Imaging Torso Phantom

Stratasys PolyJet

Walter Reed National Military Medical Center

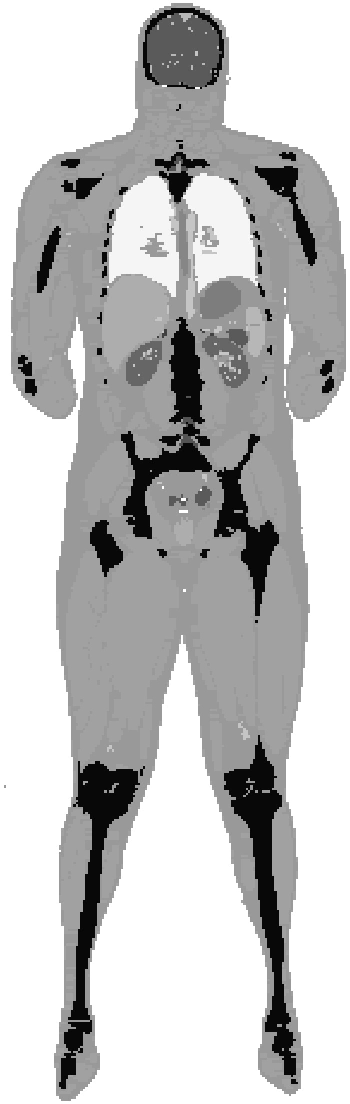






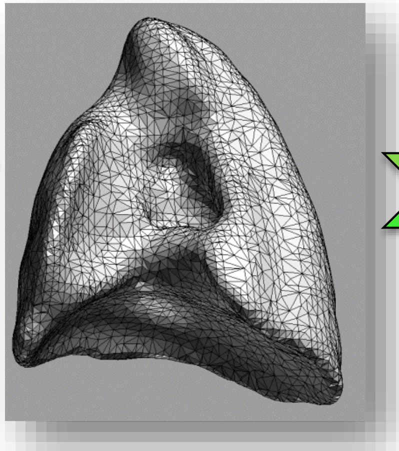
Lung Phantom For Radiobioassay

Rensselaer



NLM Visible Human Project

Mesh Model



Z-Corp Plaster Printer

Silicone Mold

Polyurethane Foam Lung

NCI Acquires Thermoplastic 3D-Printer

- Tabletop printer which extrudes heated plastic (PLA, ABS, PVA)
- Dual nozzles for printing with two plastics simultaneously
- Build volume 22 x 22 x 20 cm
- Heated build plate
- Nozzle diameter 0.25 to 0.8 mm
- Layer resolution 0.1 to 0.4 mm

1 2

Phantom Fabrication Approach

Simulate soft tissue and bones using two different plastics

Material	Physical Density	Nominal Composition	Extrusion Temperature
Polylactic Acid (PLA)	1.25 g cm^{-3}	$(C_3H_3O_2)n$	210 °C
Iron Composite PLA (PLA-Fe)	1.87 g cm^{-3}	PLA + Fe (45% iron by weight)	180 °C

Spatially vary infill to simulate realistic radiographic density

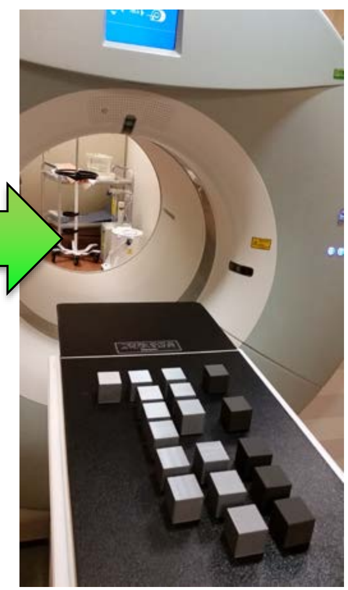
Infill Density 100% 90% 70% 50% 30%

PLA

PLA-Fe

4 cm cubes

CT Scanning At NIH



CT Images of Cubes

Abdomen Protocol, 120 kVp, 250 mAs , Pixels 0.5859 x 0.5859 x 2.0 mm

<table>
<tr><th rowspan="2"></th><th rowspan="2"></th><th colspan="5">Infill Density</th></tr>
<tr><th>100%</th><th>90%</th><th>70%</th><th>50%</th><th>30%</th></tr>
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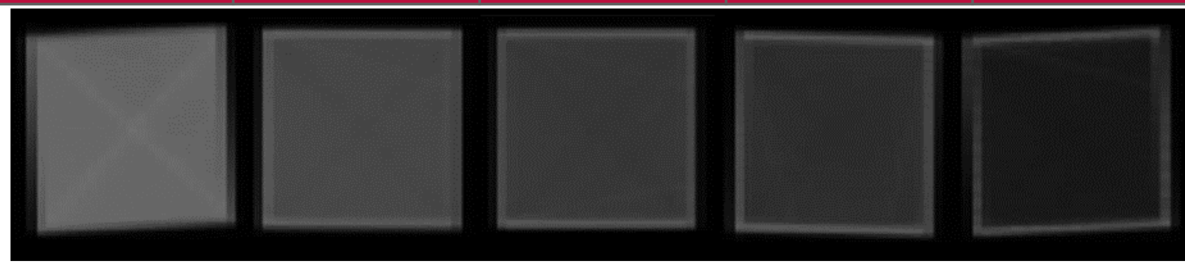
0.4 mm
nozzle</td><td>Axial</td><td colspan="5"></td></tr>
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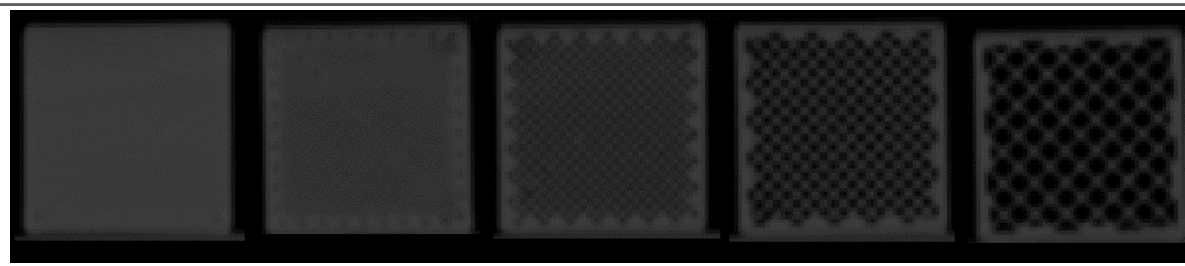
nozzle</td><td>Axial</td><td colspan="5"></td></tr>
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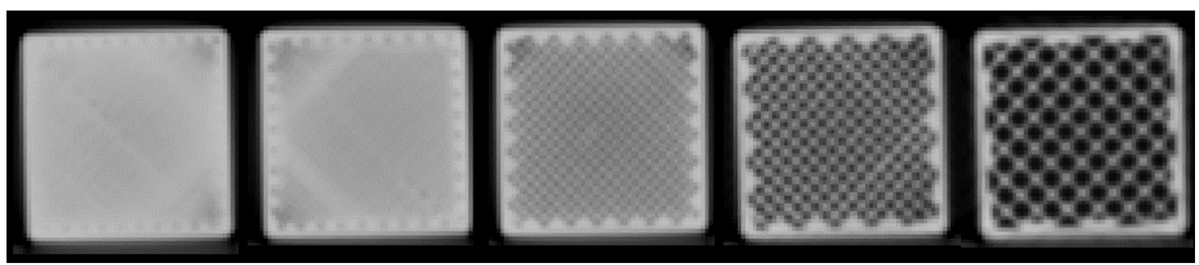
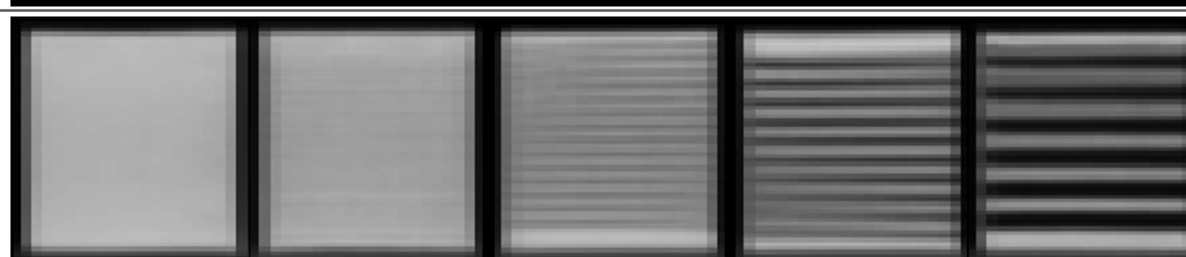
nozzle</td><td>Axial</td><td colspan="5"></td></tr>
<tr><td>PLA-Fe
0.8 mm
nozzle</td><td>Sagitta
l</td><td colspan="5"></td></tr>
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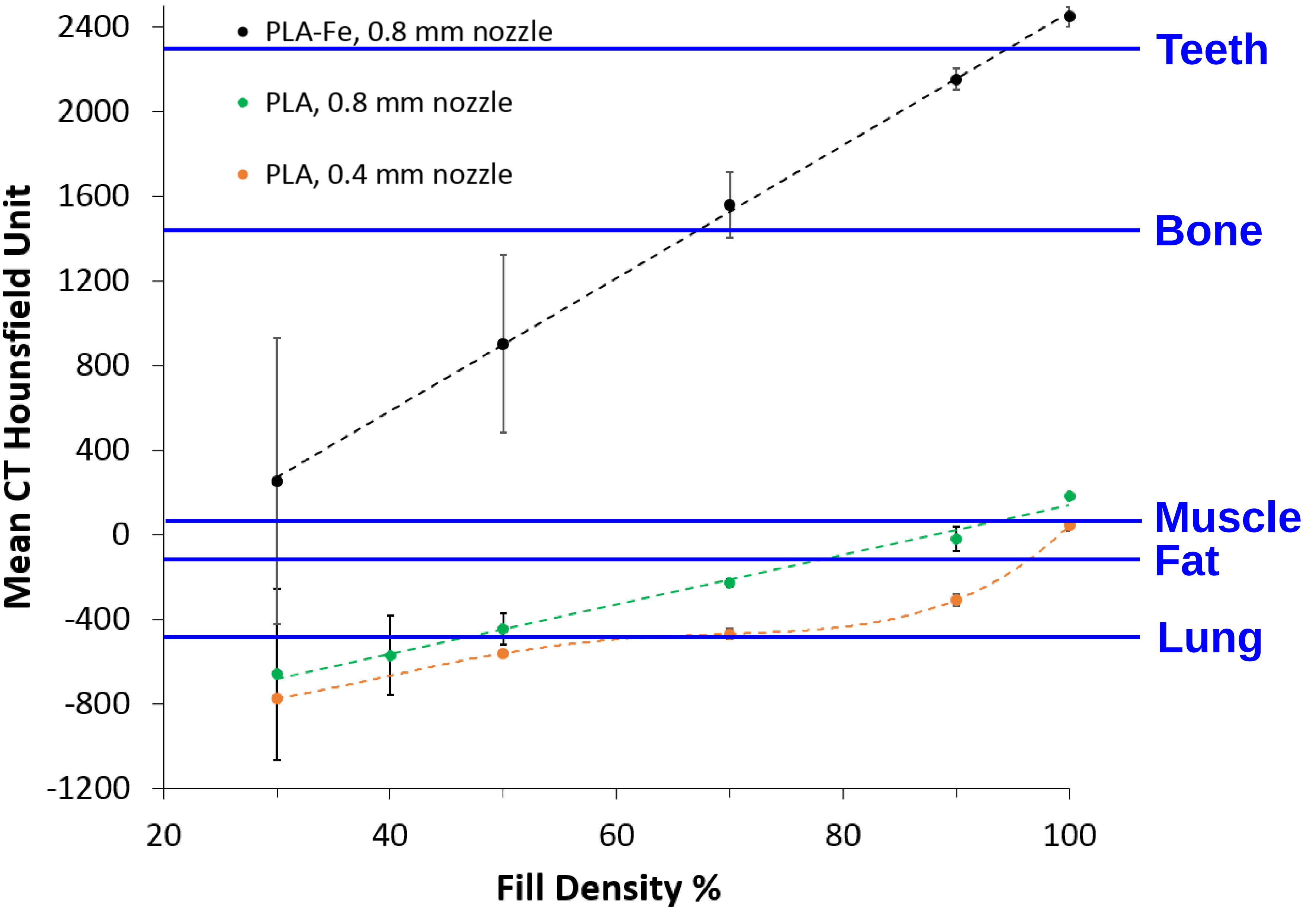
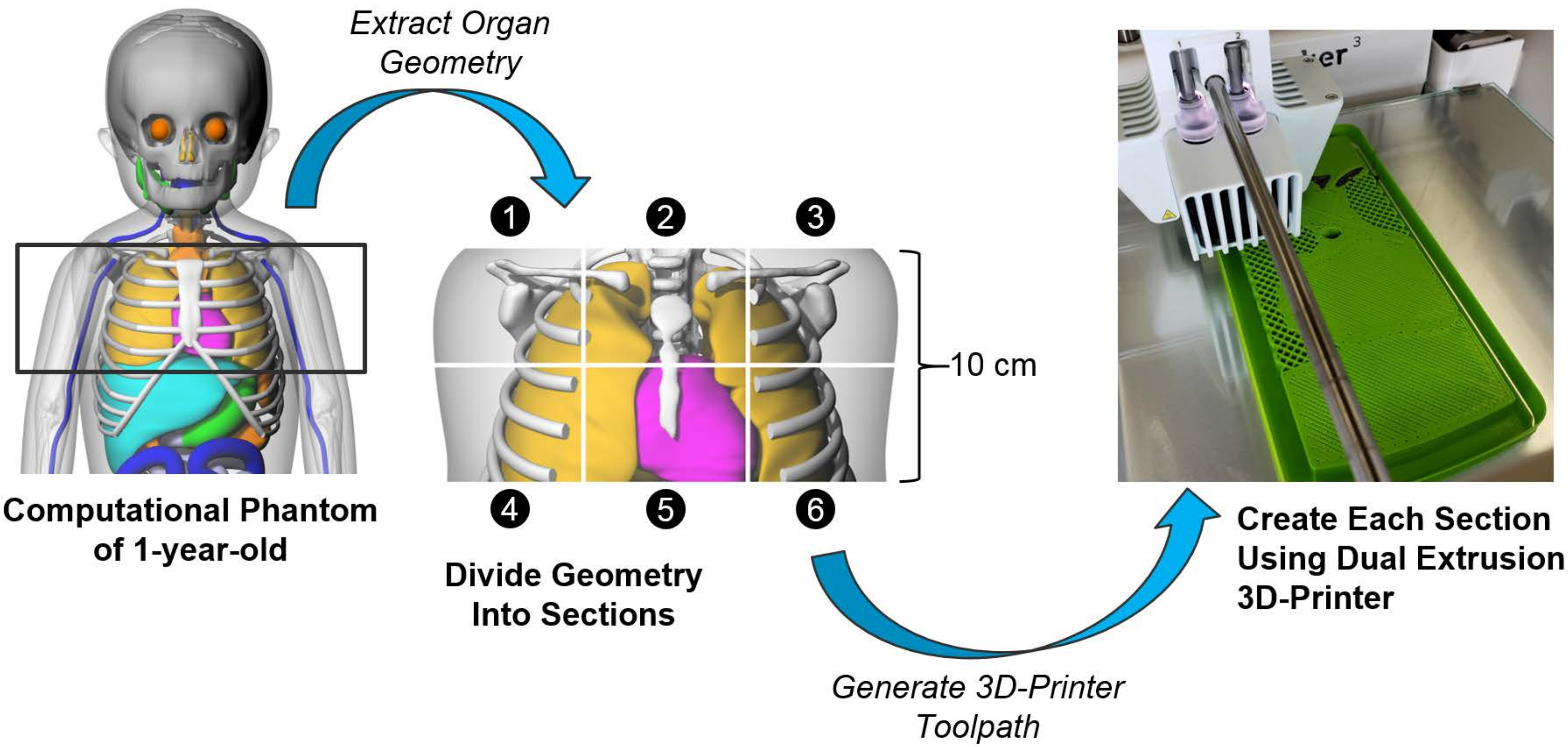
Measured CT Numbers for 3D-Printed Cubes



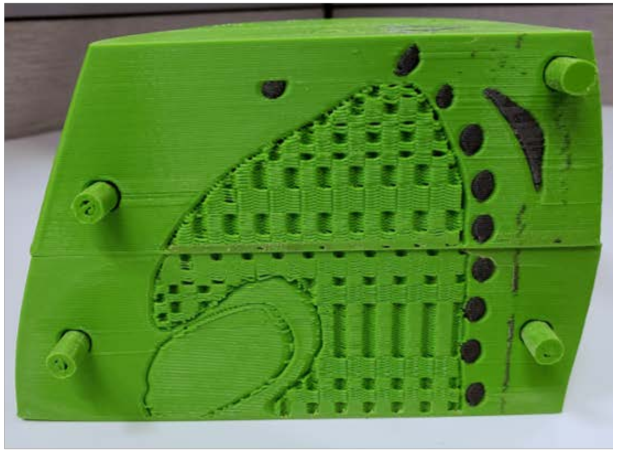
Fabrication of Pediatric Torso Phantom

Assign appropriate plastic and infill density to each anatomical region

- Over 30 anatomical structures included in model
  soft tissue remainder, lungs, heart, esophagus, ribs, clavicles, scapulae, vertebrae
- *Slic3r* (slic3r.org) open source G-code generator



3D-Printed Pediatric Torso Phantom

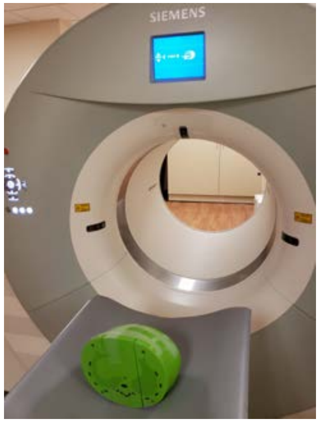


Anatomical Region	Assigned Plastic	Assigned Fill Density	Wall Thickness (mm)
Heart	PLA	100%	0.8
Soft tissue	PLA	94%	1.6
Lung	PLA	46%	0
Esophagus	Blank	-----	0.8
Skeleton	PLA-Fe	50%	1.6

Total print time ~100 hours

Estimated material cost ~$200

Verification By CT Scanning

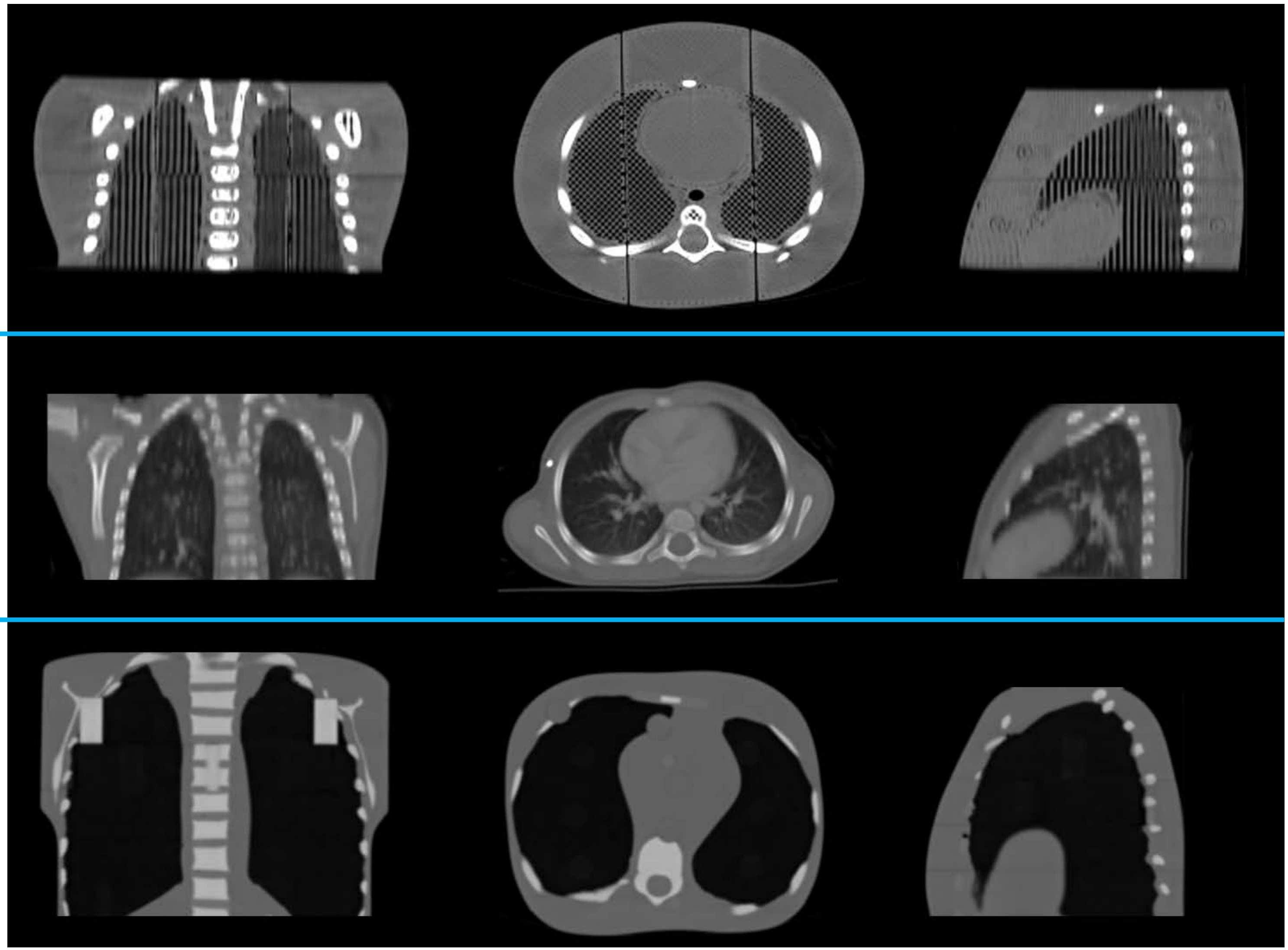


Coronal | Axial | Sagittal

3D-Printed Phantom

Patient

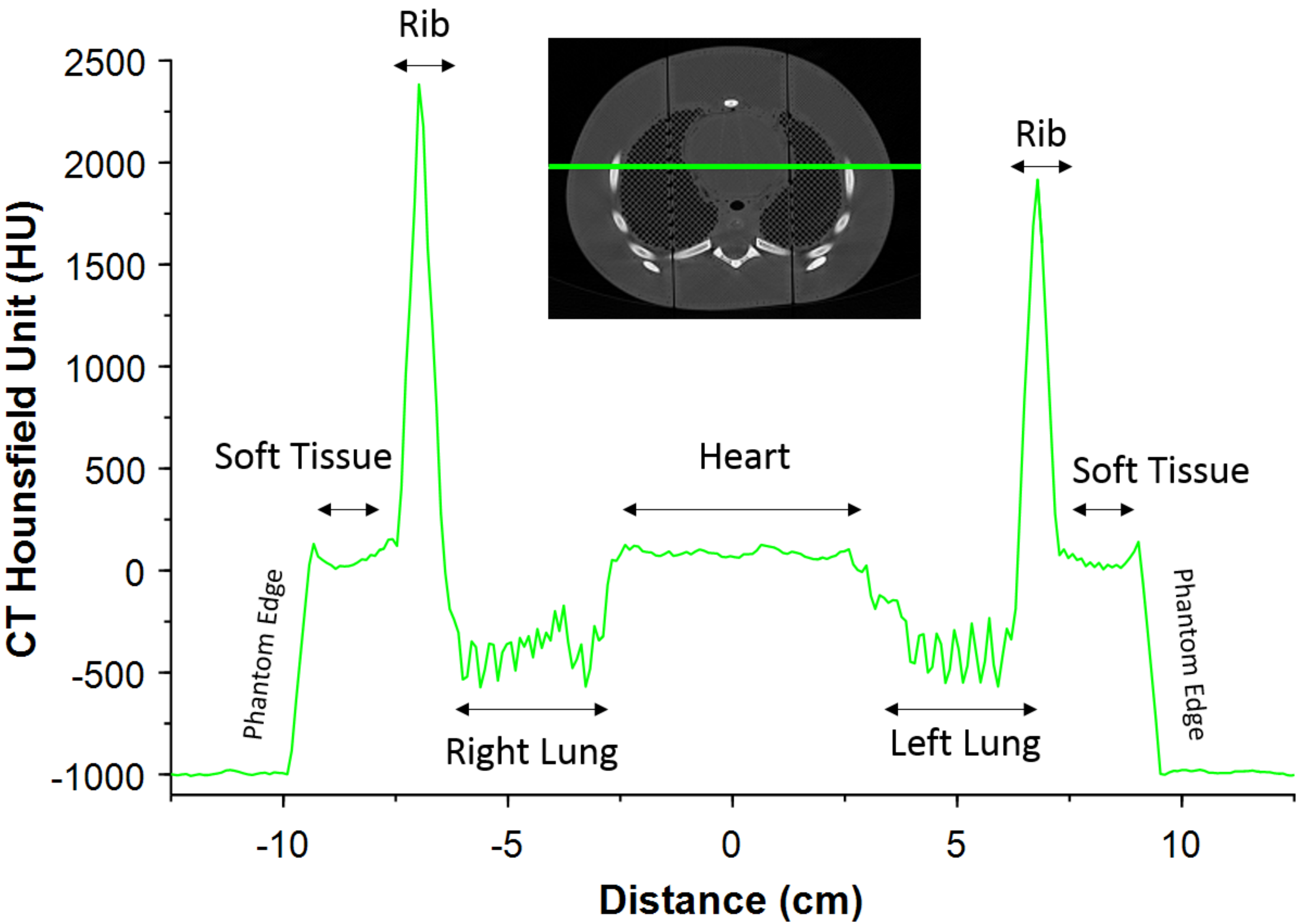
Commercial Phantom



Quantitative Comparison Of CT Numbers

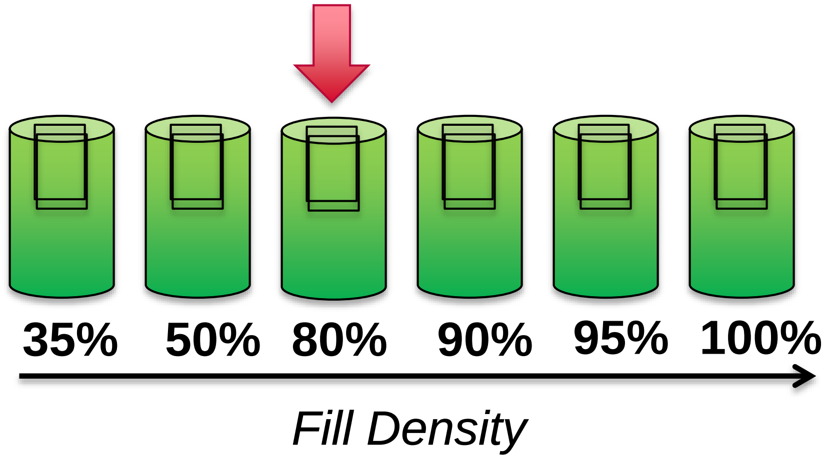
Anatomical Region	Measured Mean (Standard Deviation) CT Hounsfield Unit		
	3D-Printed Phantom	1-year-old Patient	CIRS 5-year-old Phantom
Heart	94 (46)	174 (38)	16 (33)
Soft-Tissue Remainder	31 (79)	40 (189)	19 (66)
Vertebrae Body	1180 (1107)	339 (75)	729 (52)
Scapula	1290 (1248)	373 (104)	724 (59)
Clavicle	1190 (632)	515 (337)	739 (122)
Sternum	1646 (986)	440 (83)	703 (166)
Right Lung	-417 (434)	-538 (83)	-793 (10)
Air Cavity	-904 (88)	-915 (155)	------

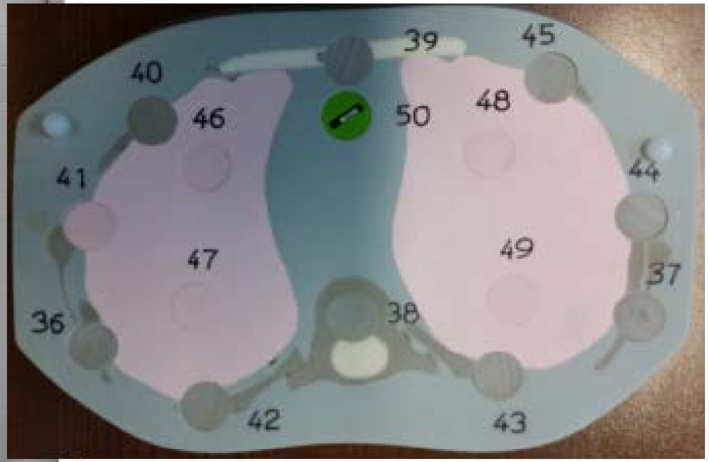
Spatially Varying Radiographic Density



Preliminary Dosimetry Measurements

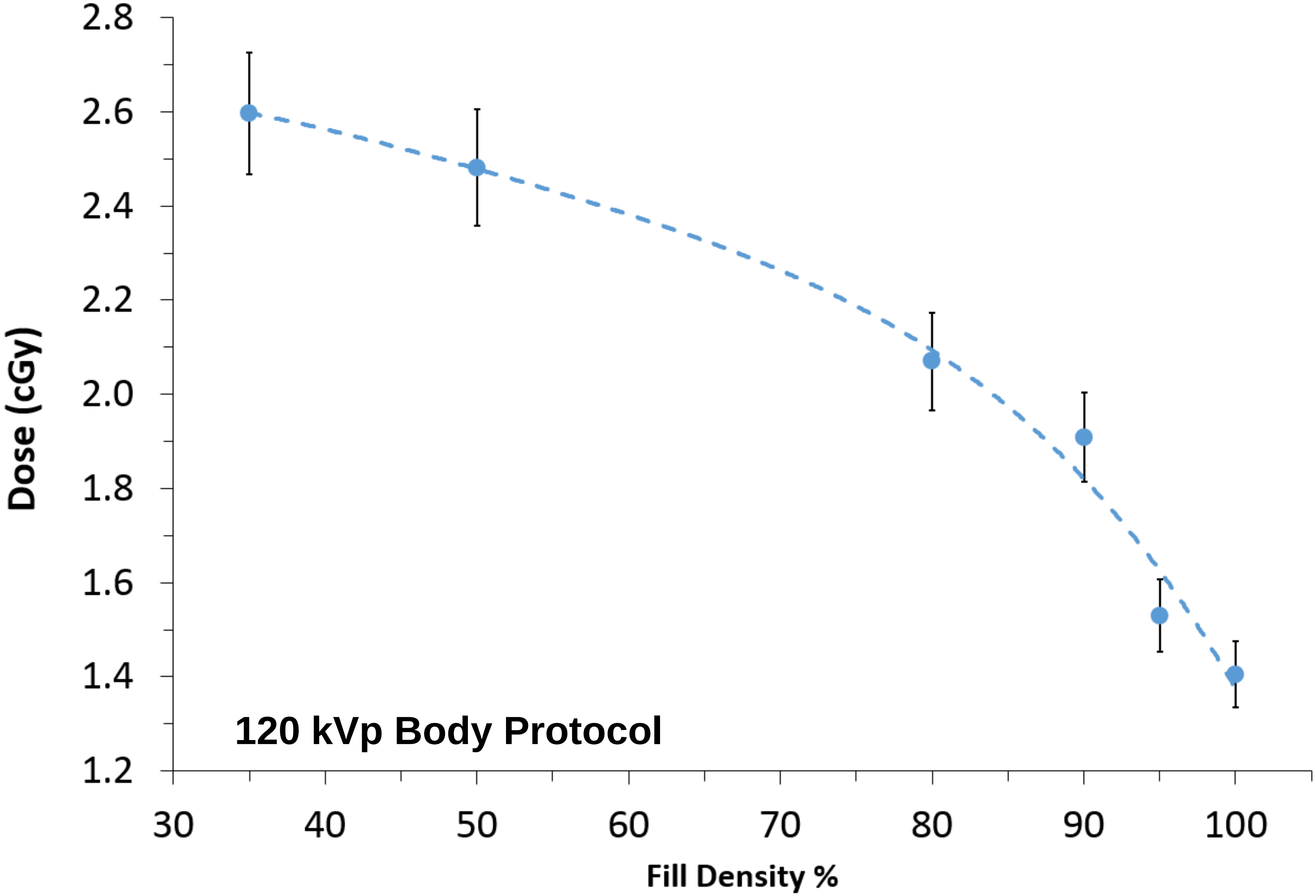
nanoDot OSL Dosimeter



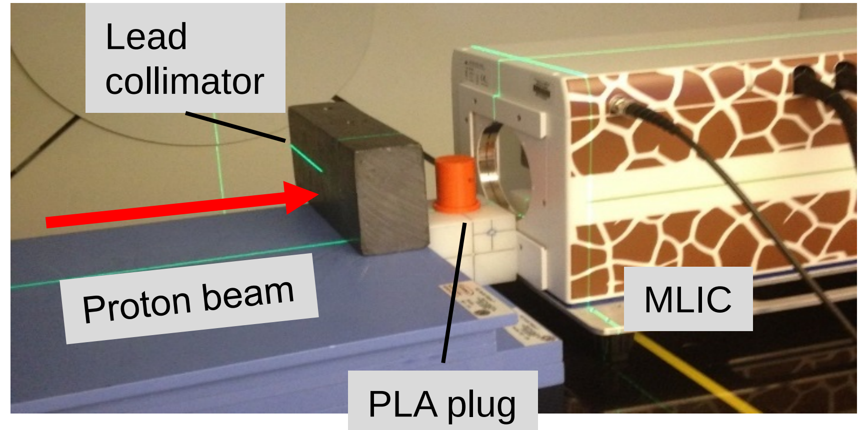


MicroStar ii Dosimetry Reader

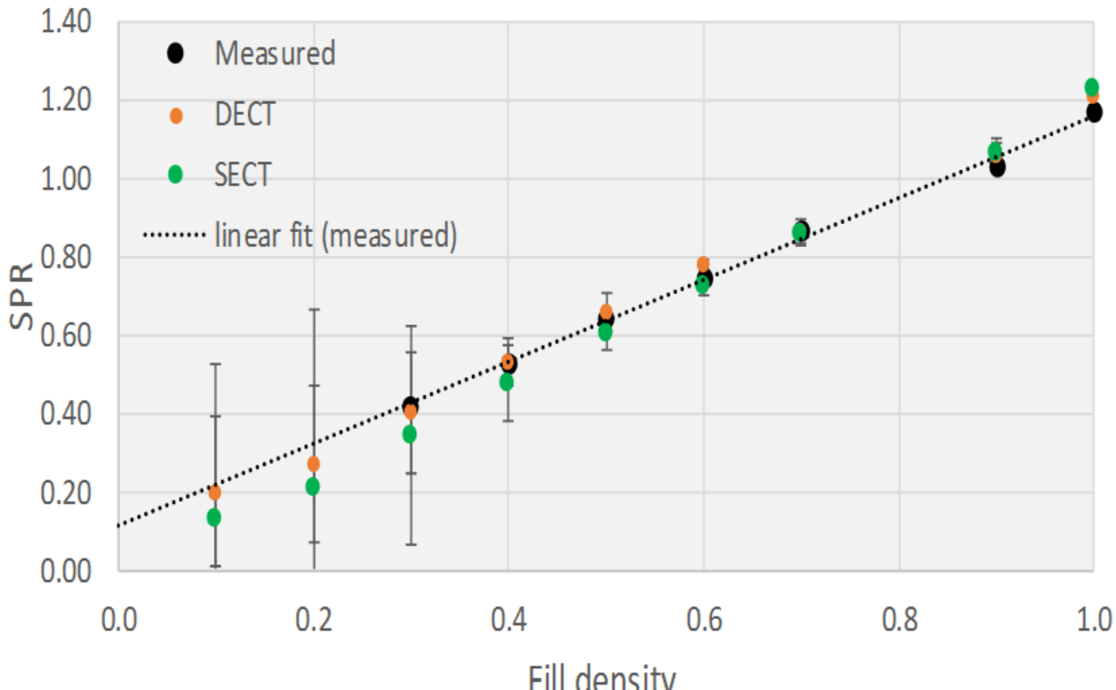
Measured Dose As A Function of Infill Density of Holder



Proton Therapy Applications



Stopping Power Ratio (SPR) Relative to Water

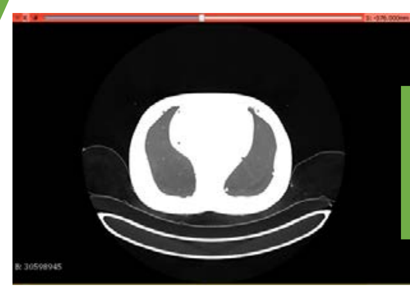


Fabrication of Obese Phantom Fat Layer For Adult Physical Phantom

CT Scanning

Patient

Phantom

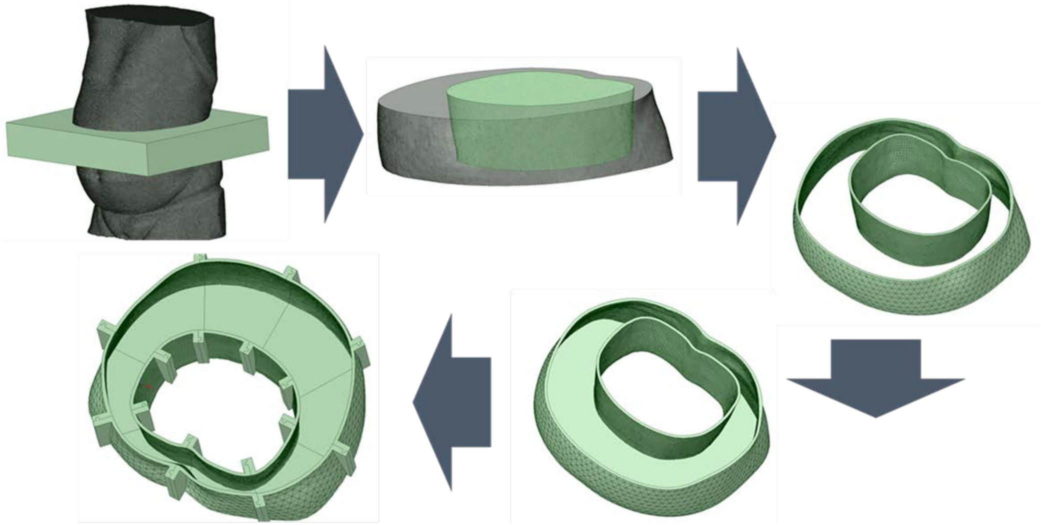


Subtract Body Contours

3D Print

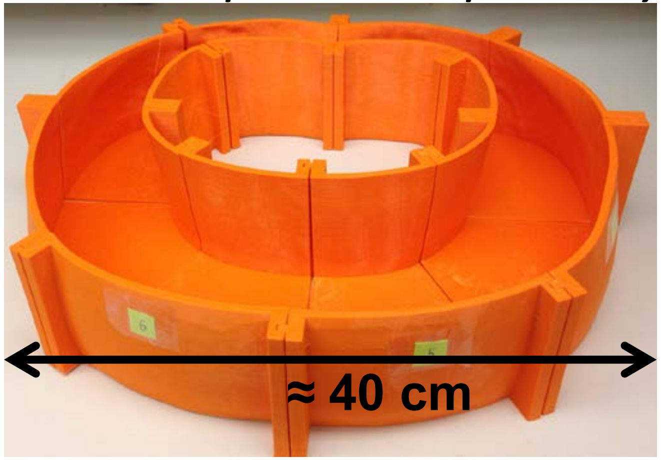
Fabrication by Molding and Casting

Computer model of fat-layer mold



3D-printed mold

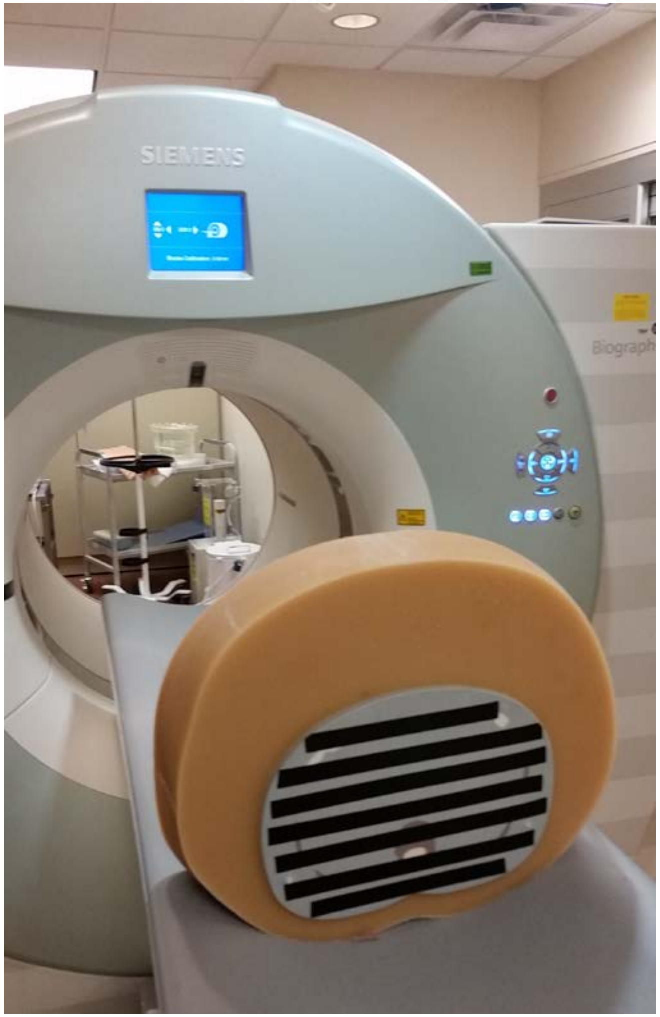
8 sections printed separately



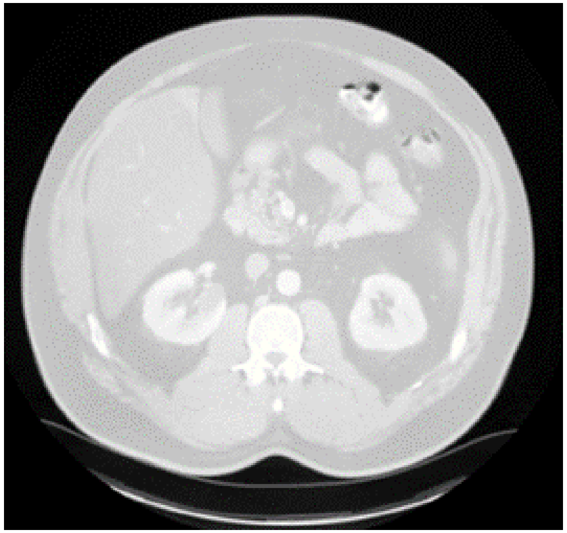
Casting using polyurethane rubber

Demolding after overnight cure

CT Scan of Obese Phantom

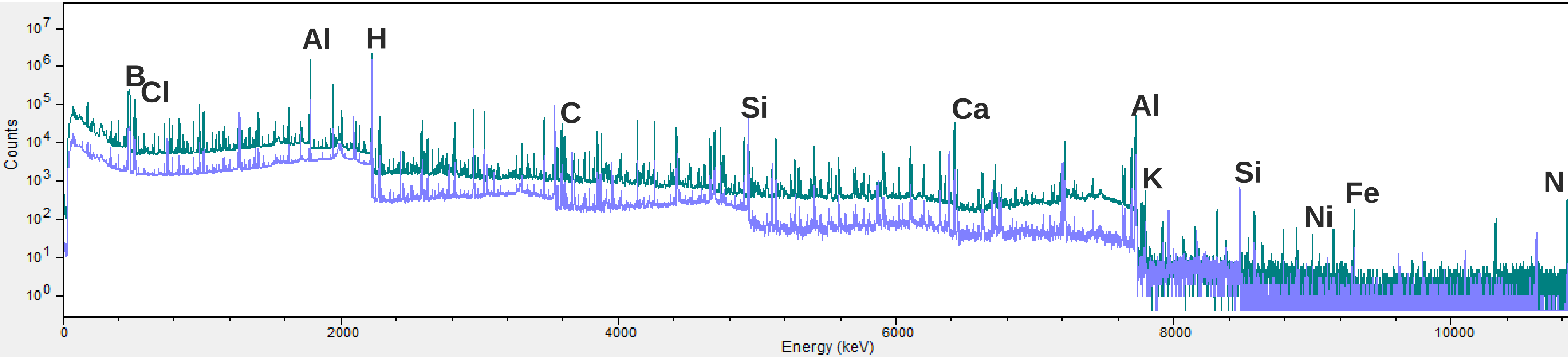


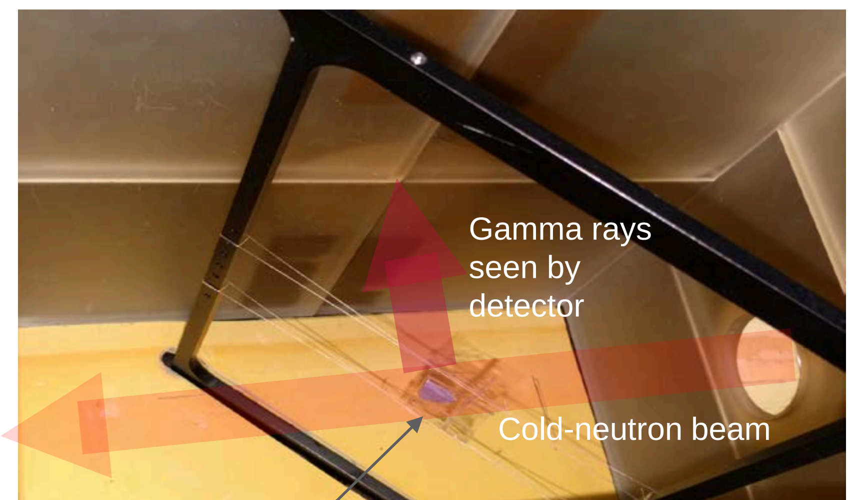
Phantom



Patient

Investigating Elemental Composition of Tissue Simulants with Prompt Gamma-Ray Activation Analysis (PGAA)





Soft Tissue Simulant

Soft Tissue Bone

"Sample prep"

Sample	Elements Identified
Soft Tissue	H, B, C, Mg, Si, Cl, Fe, Ca, Sn
Bone	H, B, C, N, Mg, Cl, Fe, Ni, Na, Ca, K

NIST

Danyal Turkoglu, Heather Chen-Mayer

Summary

- We used inexpensive printer and software to fabricate anthropomorphic phantoms by two methods
- **Direct 3D-printing of a pediatric torso**
  Design on computer and create by push of a button
- **Fabrication of Fat Layer Using 3D-printed mold**
  More efficient for large-volume parts, but not automatic
- Materials, printer build-size, and speed are limiting factors but can be overcome
  - Life-size phantoms can be printed in sections
  - Using multiple materials and vary infill density
  - New composite materials for simulating bone
  - No 3D-printing material to simulating lung

Conclusions

- 3D-printing shows great promise for the on-demand fabrication of patient-specific phantoms
- Our work has shown that much can be accomplished despite the limitations of current technology
- Future efforts will focus on development of customized materials and software solutions for improving our results

3D Printing Gone Wrong!