MAYO CLINIC

Patient Specific Imaging Phantoms Using 3D Printing

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Phantom

- **Imaging phantom**, or simply **phantom**, is a specially designed object that is scanned or imaged in the field of medical imaging to evaluate, analyze, and tune the performance of various imaging devices.
  - Wikipedia



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QC Phantoms

- Evaluate system performance: ensure scanners perform appropriately
- Assess image quality and radiation dose
- Simple, defined shape – not patient like




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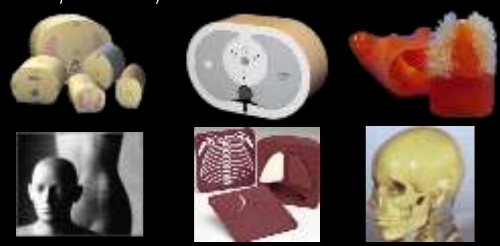
Anthropomorphic Phantoms

- Phantoms mimic human body properties (‘*patient like phantoms*’)



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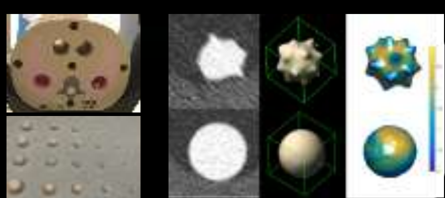
Anthropomorphic Phantoms

- Used to evaluate image quality, scanning techniques, reconstruction algorithms …



Zhou *et al*, Lung Nodule Volume Quantification and Shape Differentiation with an Ultra-High Resolution Technique on a Photon Counting Detector CT System. *J. Med. Img.*, 2017

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Anthropomorphic Phantoms

- Standard set, hard to customize
- Usually expensive
- Details and textures are simplified compared to patient anatomies
- Not specific to the patient or cohort of interest.
  – Need of patient-specific phantom

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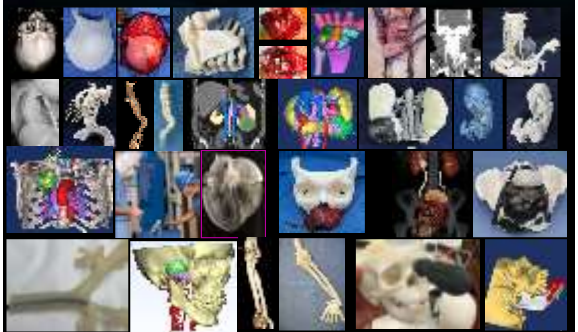
3D Printing in Medicine



Benefits of 3D Printing in Phantoms

- Easy to customize, short turnaround time
- Capable of patient specific phantom
- Complicated geometry and structures, great details
- High accuracy and fidelity

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Print Technology

Material Extrusion	FDM: Heated nozzle used to extrude mostly thermoplastics to create successive object layers.
Vat Photopolymerization	SLA: Laser or other light source to solidify successive object layers on the surface or base of a vat of liquid photopolymer.
Material Jetting	Polyjet: Uses multiple print heads to spray liquid layers that are solidified by exposure to UV light
Binder Jetting	Uses a print head to selectively spray a binder (glue) onto successive layers of power
Powder Bed Fusion	SLS: EBM: uses a laser, electron beam or other heat source to selectively fuse successive powder layers. Plastics and Metals
Direct Energy Deposition	Metal Printing: laser or other heat source to fuse a powdered build material as it is being deposited.
Sheet Lamination	Paper Printer, Metal Printer: sticks together sheets of cut paper, plastic or metal.

3D Printing of Phantoms

- 3D printers were not designed to print imaging phantoms
- Special requirement of 3D Printed Phantoms
  - Geometric accuracy and resolution
  - Appropriate imaging properties
    - *Attenuation property in X-ray & CT*
    - *T1, T2, Proton density in MRI*
    - *Sound propagation in US (impedance)*
  - Other considerations
    - *Stability, Cost, Printing time*

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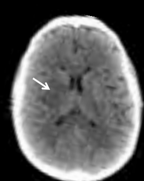
3D printing process

CT patient data → Segmentation → Material selection → 3D printing

- CT images of patient with acute cerebral infarction
  - 38 mGy $CTDI_{vol}$
  - Medium sharp reconstruction kernel (J40) at 2 mm slice thickness
- Hypo-attenuation of the lentiform nucleus due to acute stroke



Chen et al, RSNA, 2016

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3D printing process

CT patient data → Segmentation → Material selection → 3D printing

- Segmentation software to generate voxelized phantom
  - Commercial software
  - Free software

- Computer aided design software to generate STL files (mesh processing)

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3D printing process

- CT patient data
- Segmentation
- Material selection
- 3D printing

- Printer selection
  - Objet 350 Connex (Stratasys, MN)
  - PolyJet additive manufacturing:
    - Photopolymers cured by UV light
  - 600 × 600 × 1600 dpi
  - 350 × 350 × 200 mm

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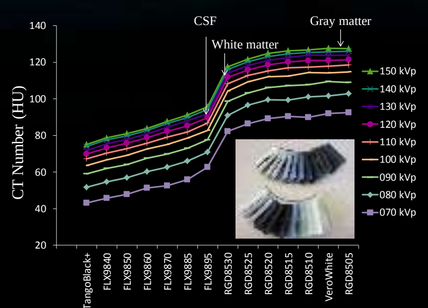
3D printing a brain phantom

- CT patient data
- Segmentation
- Material selection
- 3D printing



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3D printing a brain phantom

- CT patient data
- Segmentation
- Material selection
- 3D printing

- STL file sent to 3D printer
- Cleaning after printing
- Final phantom
  - only a center cylindrical portion was printed
  - 10 x 10 x 6 cm
  - around $300
  - a few hours of printing time

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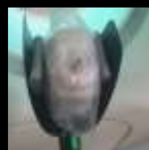
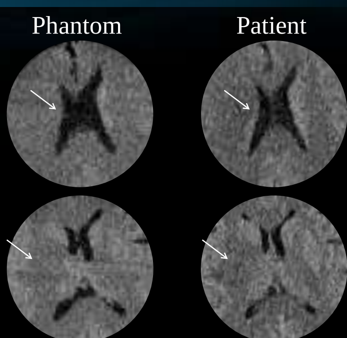
Validation

- Printed phantom placed within a human skull embedded in acrylic
- Scanned on a 192-slice CT scanner (Definition Force, Siemens) using a routine head protocol





Validation



White matter: 125 HU

Gray matter: 134 HU

CSF: 108 HU

Liver Phantom

Contrast enhanced liver CT scan

Vessels, tumor

2 materials for liver tissue (heterogeneous background)

Leng *et al*, AAPM, 2014

Printed Phantom

- Create and print hollow vessels
- Filled with iodine solutions, adjust concentration to mimic different levels of vessel enhancement

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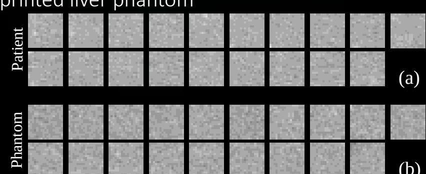
Texture Analysis

- Similar background texture between patient and printed liver phantom



	Patient images	Phantom images
Homogeneity	0.94 ±0.01	0.90±0.01
Energy	0.64±0.07	0.41±0.05
Correlation	0.51±0.05	0.57±0.03
Contrast	0.13±0.02	0.19±0.02
Entropy	0.78±0.12	1.12±0.07

Leng *et al*, Construction of realistic phantoms from patient images and a commercial three-dimensional printer. *JMI*, 2016

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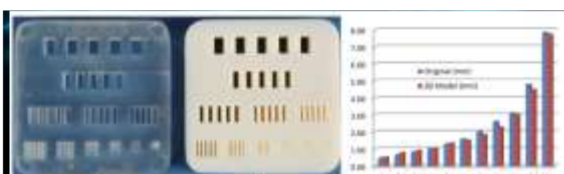

Geometric Accuracy

Leng et al, *Anatomic modeling using 3D printing: quality assurance and optimization*, 3D Printing in Medicine, 2017

FDM 3D Printer

- FDM 3D Printing
  - Thermoplastic filament is fed into a heated extrusion nozzle producing melted plastic.
  - Less expensive printer
- Num. of materials determined by # of heads
- Most 3D printed parts are concerned with surface appearance and contain interior scaffolding to save material and cost.
- The printing code was modified to ensure a solid fill throughout the phantom.

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Filaments

- The vast majority of filaments are plastic-based, with CT number in the range of 0-200 HU
  - Need for higher attenuating materials, Bone: ~1000 HU
- Materials with metal powder have higher CT numbers
  - PLA containing stainless steel powder (ssPLA): 5250 HU
- Customized material mixtures:
  - White PLA: 160 HU & ssPLA
  - Various attenuation obtained by changing mixing ratio

$$\mu_{mix} = \frac{1}{\alpha\rho_2 + (1-\alpha)\rho_1}(\alpha\mu_1\rho_2 + (1-\alpha)\mu_1\rho_2)$$

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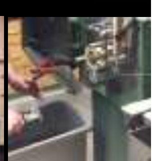
Filament Manufacturing

Pelletizer

Mixer and Extruder



1.75 mm diameter filaments with different attenuations

Vanoosten *et al*, RSNA, 2017

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Printed Phantom

- Wrist CT images segmented into bone and soft tissues.
- Model was printed with the customized filament to mimic the attenuation of the wrist CT images.

Vanoosten *et al*, RSNA, 2017

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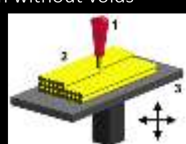
Challenges Using FDM Technology

- Desk top printer – not always plug and play
- Number of materials limited
  - No material mixing on the fly
- Difficult to print solid phantom without voids
  - Printing temperature
  - Filament uniformity
  - Extrusion speed (fill rate)
  - Ooze control
- Filament manufacturing



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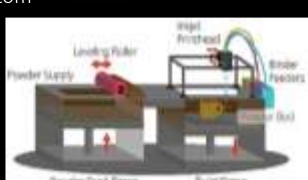
Powder-Binder based Printer

- Creates three dimensional objects by solidifying layers of deposited powder using a liquid binder.
- Modify binders allow change properties of printed phantom



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Anatomically Realistic PET & PET/CT Phantoms

- Z510 printer, A cellulose based powder (zp15e)
- By adding radioactive dyes to the binder, parts with highly detailed distributions of radioactivity can be produced.
- No need for segmentation

Miller and Hutchins, Development of Anatomically Realistic PET and PET/CT Phantoms with Rapid Prototyping Technology. IEEE NSS, 2007

Anatomically Realistic PET & PET/CT Phantoms

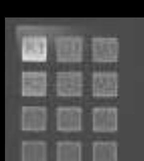
CT PET PET/CT

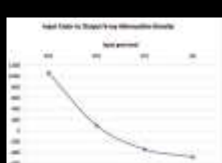
Density of the cellulose based powder is ~0.5 g/mL, with an x-ray attenuation coefficient that results in CT# ~ -600.

Miller and Hutchins, Development of Anatomically Realistic PET and PET/CT Phantoms with Rapid Prototyping Technology. IEEE NSS, 2007

X-Ray CT Phantom

- Zp15e powders: no calcium, made with only light organic compounds
- Amended the liquid with high concentrations of sodium iodide (NaI).





Yoo *et al*, Toward quantitative X-ray CT phantoms of metastatic tumors using rapid prototyping technology, IEEE, ISBI, 2011

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X-Ray CT Phantom

- Successful 2½D tests
- Require a 3D test pattern and a better API for communicating with the printer.

Yoo *et al*, Toward quantitative X-ray CT phantoms of metastatic tumors using rapid prototyping technology, IEEE, ISBI, 2011

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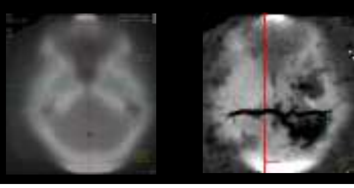
Challenges

- Powder with low attenuation not available any longer, current powder gypsum based
- Software modification needed (binder only to the exterior of the part)
- Fix phantom after printing



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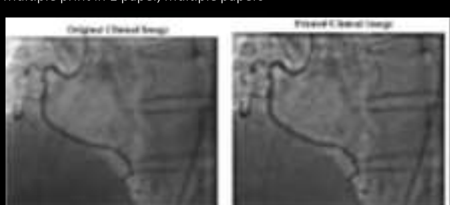
Paper Phantom – Planar X-ray Phantom

- Standard inkjet printer, but using potassium iodide solution (1000 g/l) in place of the cartridge's ink.
- Thick A4 paper (0.2 mm)
- Multiple print in 1 paper, multiple papers



Theodorakou *et al*, A novel method for producing x-ray test objects and phantoms. PMB, 2004

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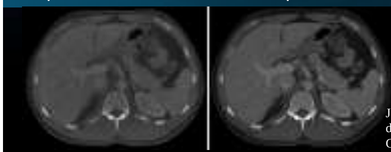
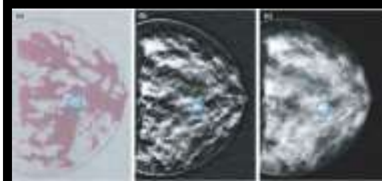
Paper Phantom – 3D phantoms



Jahnke *et al*, Radiopaque Three-dimensional Printing: A Method to Create Realistic CT Phantoms. Radiology, 2016



Ikejimba *et al*, A novel physical anthropomorphic breast phantom for 2D and 3D x-ray imaging, Med. Phys. 2017

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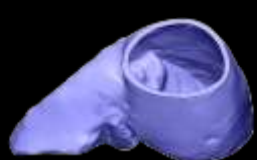
3D Printed Phantoms in MRI and US

- Printing materials don't have appropriate MRI and US signals

Hollow 3D liver model



3D printed hollow liver

Courtesy Dr. Kiaran McGee

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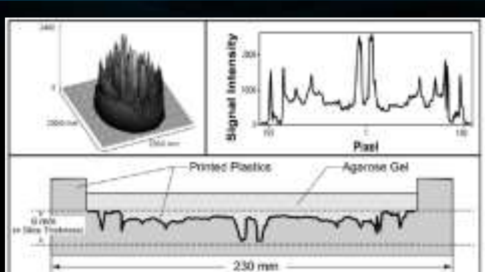
MRI Phantoms



Saotome et al, A brain phantom for motion-corrected PROPELLER showing image contrast and construction similar to those of in vivo MRI. MRM, 2017

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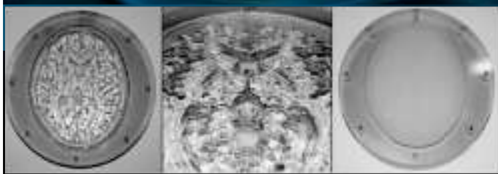

Saotome et al, A brain phantom for motion-corrected PROPELLER showing image contrast and construction similar to those of in vivo MRI. MRM, 2017

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US Phantoms

- Two materials mimicking bone and ligament
- Lack of soft-tissue materials
- Printed phantom placed in agar solutions

West et al, Development of an Ultrasound Phantom for Spinal Injections With 3-Dimensional Printing. Regional Anesthesia and Pain Medicine, 2014

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Applications of 3D Printed phantom

- System optimization
- Image quality assessment
- Evaluate new reconstruction techniques
- Radiation dose reduction
- Novel clinical applications
- Training and education
- …

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Evaluate Image Quality and Dose Reduction

- Clinical questions:
  - What is the lowest dose w/o sacrificing diagnosis?
  - How much dose reduction is possible?
- Can't scan patients repeatedly
- Use 3D printed phantom
  - Scanned on a CT scanner and reconstructed using FBP and Iterative Reconstruction

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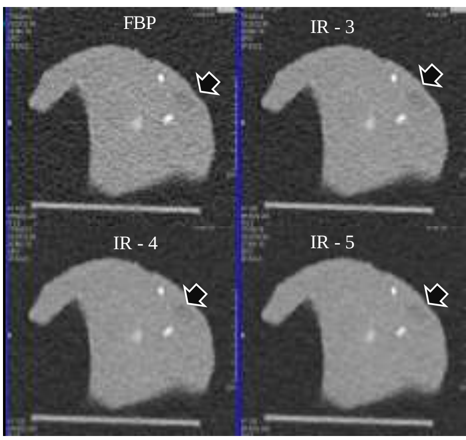

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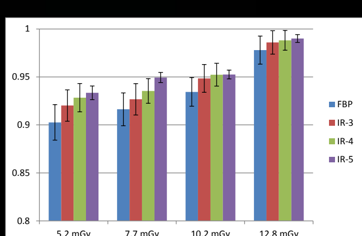
Evaluate Image Reconstruction Algorithms

- Liver lesion detectability using the 3D printed phantom



Leng *et al*, Construction of Realistic Liver Phantoms from Patient Images using 3D Printer and Its Application in CT Image Quality Assessment, SPIE, 2015

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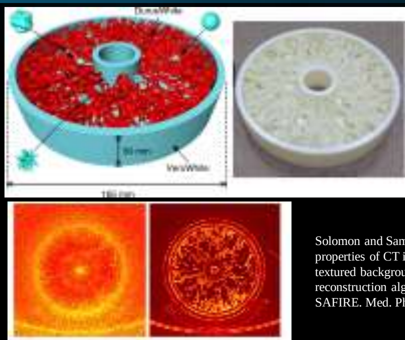
Noise Texture Analysis



Solomon and Samei, Quantum noise properties of CT images with anatomical textured backgrounds across reconstruction algorithms: FBP and SAFIRE. Med. Phys. 2014

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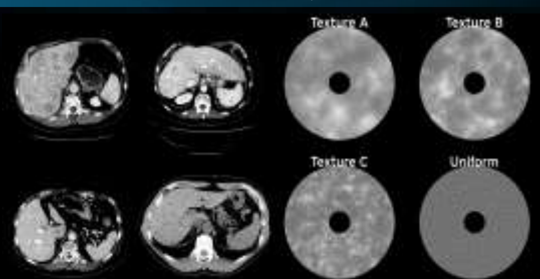
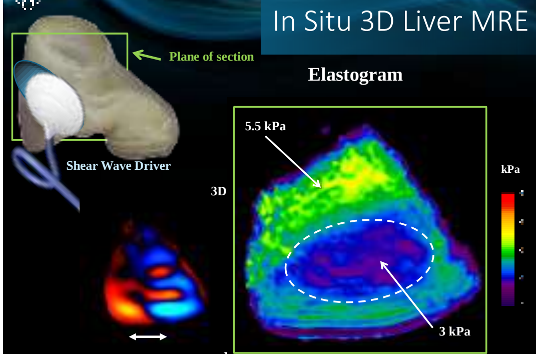
Textured Phantom Library



Solomon J, et al. Comparison of low-contrast detectability between two CT reconstruction algorithms using voxel-based 3D printed textured phantoms. *Medical Physics*, 2016.

Images Courtesy Dr. Samei

In Situ 3D Liver MRE



Courtesy Dr. Kiaran McGee

Summary

- 3D printing has high potential to print patient-specific, anatomic phantoms with complex and realistic textures.
- Different printer and printing techniques can be used, each with pros and cons
  - Photopolymer
  - FDM
  - Power-Binder
  - Paper-based
- Modification is needed for most of the printers to print imaging phantoms
- High resolution and geometric accuracy

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Summary

- Opportunities and Challenges
  - Printing materials for each modality
    - X-ray/CT: High attenuating; Low attenuating
    - MRI and US
  - Gray scale levels and gradient
    - Number of materials
    - Continuous gradient
  - Printing mode: Object vs Bitmap
  - Cost and printing time
  - Software support and printer communication

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  - Kiaran McGee,
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Thank You!
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