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.

QC Phantoms

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

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

• Used to evaluate image quality, scanning techniques, reconstruction algorithms ...


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
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

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**
  - SLS: Uses a print head to selectively spray a binder (glue) onto successive layers of powder
- **Powder Bed Fusion**
  - 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

3D printing process

> CT images of patient with acute cerebral infarction
  - 38 mGy CTDIvol
  - 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

3D printing process

> Segmentation software to generate voxelized phantom
  - Commercial software
  - Free software
> Computer aided design software to generate STL files (mesh processing)
3D printing process

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

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

3D printing a brain phantom

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

3D printing a brain phantom

- 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

STL file sent to 3D printer → Cleaning after printing → Final phantom

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

Final phantom

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- 10 x 10 x 6 cm
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CT Number (HU)

<table>
<thead>
<tr>
<th>CT Number (HU)</th>
<th>Material</th>
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<tbody>
<tr>
<td>20</td>
<td>TangoBlack+</td>
</tr>
<tr>
<td>40</td>
<td>FLX9840</td>
</tr>
<tr>
<td>60</td>
<td>FLX9850</td>
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<tr>
<td>80</td>
<td>FLX9860</td>
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<td>120</td>
<td>FLX9885</td>
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<td>RGD8530</td>
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<td>RGD8510</td>
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<td>240</td>
<td>RGD8505</td>
</tr>
</tbody>
</table>

CSF

Gray matter

White matter

CT Number (HU)
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

Phantom vs. Patient

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

Texture Analysis

- Similar background texture between patient and printed liver phantom

<table>
<thead>
<tr>
<th></th>
<th>Patient</th>
<th>Phantom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneity</td>
<td>0.94 ± 0.01</td>
<td>0.90 ± 0.01</td>
</tr>
<tr>
<td>Energy</td>
<td>0.64 ± 0.07</td>
<td>0.41 ± 0.05</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.56 ± 0.06</td>
<td>0.57 ± 0.03</td>
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<tr>
<td>Contrast</td>
<td>0.13 ± 0.02</td>
<td>0.19 ± 0.02</td>
</tr>
<tr>
<td>Entropy</td>
<td>0.78 ± 0.12</td>
<td>1.12 ± 0.07</td>
</tr>
</tbody>
</table>

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

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.

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
  \[ \mu_{\text{mix}} = \frac{1}{a\mu_1 + (1-a)\mu_2} \left( a\rho_1 \mu_2 + (1-a)\mu_1 \rho_2 \right) \]

Filament Manufacturing

- Pelletizer
- Mixer and Extruder

1.75 mm diameter filaments with different attenuations

Vanoonen et al. RSNA, 2017
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

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

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
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

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
**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*

**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

**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*
Paper Phantom – 3D phantoms


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

Agarose gel

Courtesy Dr. Kieran McGee

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

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

Applications of 3D Printed phantom

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

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

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

Textured Phantom Library


Images Courtesy Dr. Samei

In Situ 3D Liver MRE

Elastogram

Courtesy Dr. Kieran 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
  - Powder-Binder
  - Paper-based
- Modification is needed for most of the printers to print imaging phantoms
- High resolution and geometric accuracy

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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