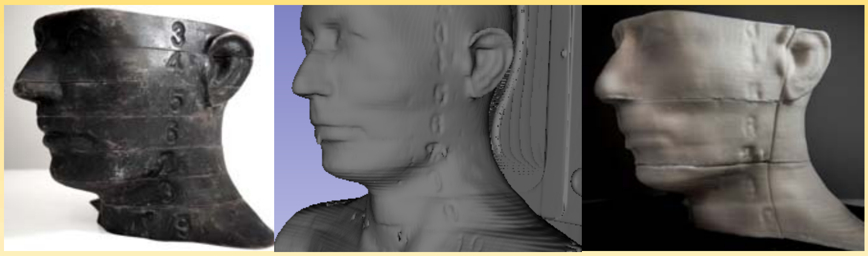
Creation of 3D printed phantoms for clinical radiation therapy



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UNIVERSITY OF MINNESOTA
Driven to Discover℠

Overview

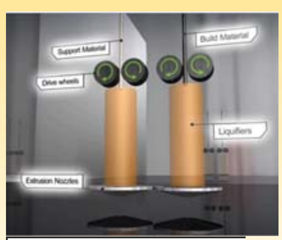
- Background of 3D Printing
- Practical Information
- Current Work
- Areas of future improvement

Technologies

- Fused Deposition Modelling (FDM) – Most Common
  - Cheapest
  - Most consumer grade printers are FDM
- Stereolithography (SLA)
  - Easier to print with heterogeneous materials
  - Costly
  - Can accommodate more than 20 material types in one print

Modalities

- Fused Deposition Modelling
  - Material is melted
  - Then extruded out a nozzle → a layer is deposited
  - Material cools and hardens
  - Next layer is deposited top layer cools to bottom → fused!



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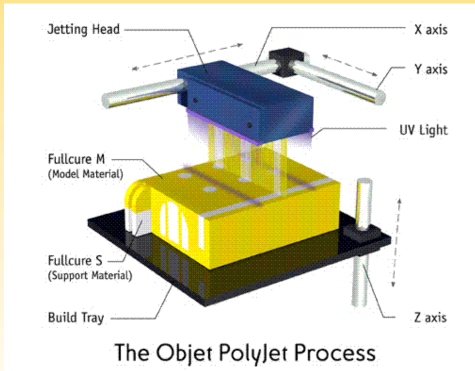
Modalities

- Stereolithography
  - A photopolymer is hardened with a light
    - Many light sources are UV spectrum
  - Either have a vat of photopolymer or spray it out of a nozzle



3D Printers - available

- Fused Deposition Modelling
  - $ 100s to $10,000s for the printer
  - Material Costs, $30-$100 per kg ($15 per lb)
- Stereolithography
  - $5,000 to $600,000 for the printer

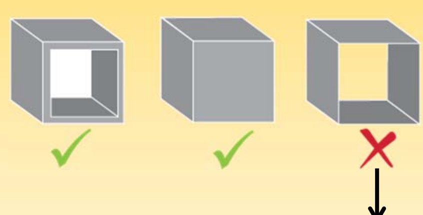
3D Printing Accuracy

- Printing accuracy on par with radiotherapy?
  - FDM example - Ultimaker 2
    - 20 µm layer thickness / 13 x 13 x 5 µm positional accuracy
    - 0.4 mm nozzle diameter (0.2 mm available on other printers)
  - SLA
    - 0.025 – 0.05 mm per 25.4 mm
    - SLA lacks high temperatures so less warping
    - Easier to achieve high spatial fidelity
  - Other things to consider
    - Thermal shrink, Warping of printer and print object (FDM)
    - Accuracy of 3D Model (Typical CT 1 mm x 1 mm x 3 mm)

Practical Information

- Start with a good 3D Model

Model must be volumetric



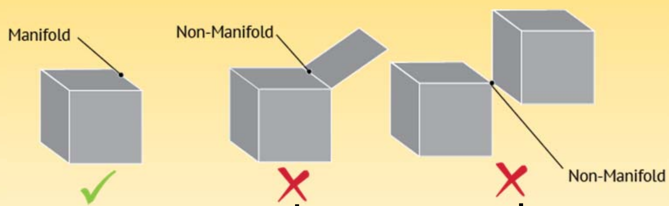
Walls have no volume – can not be 3D printed

http://www.sculpteo.com/en/repair-your-file-3d-printing

Practical Information

- Start with a good 3D Model

No non-manifold edges or points



One edge, three faces

Two surfaces connected at only one point

http://www.sculpteo.com/en/repair-your-file-3d-printing

Why 3D Printing?

- 3D Modelling Software

Design 3D Model

Blender
AutoCAD
OpenSCAD
Google Sketchup

Create 3D models from stacks of 2D image data

3D Slicer
Mimics

Create 3D models from 3D scanners

Sense / iSense
Skanect 3D
ReconstructMe
kScan3D
Artec 3D

Modify / Repair 3D Models

NetFabb
Blender
Google Sketchup

Why 3D Printing?

- Advantages
  - 3D Printing excels at Custom fabrication
    - Lower cost for Prototype fabrication
      - Great when you only need 1 unit of something
    - Fast fabrication process
      - Just need a good 3D model
    - Less waste than traditional methods – i.e. CNC, subtractive mfg.
      - Good if you are working with expensive materials
- Disadvantages
  - 3D Printing is inferior when you need 10,000 of same thing

Why 3D Printing?

- Advantages
  - 3D Printing excels at Custom fabrication
- Disadvantages
  - 3D Printing is inferior when you need 10,000 of same thing
- Patient specific devices
  - Rarely do patients have identical anatomy
  - Find cases where patient specific devices provide an advantage

Custom Fabrication

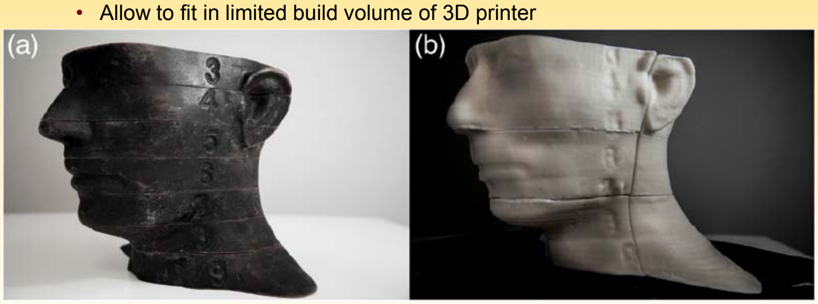
- Patient specific devices
  - Could patient specific QA benefit from patient specific phantoms?
    - Is there an advantage over universal designed phantoms?
    - Ultimate QA goal: Understand the actual dose delivered to the patient

Patient Planned Dose
↓
Recalculate dose on a standard phantom (cylinder, cube, etc.)
↓
Measure dose in phantom
↓
Reconstruct the dose difference to determine impact of dose accuracy

Patient Planned Dose
↓
3D Print Patient Specific phantom
↓
Measure dose to patient specific phantom using actual immobilization devices & localization systems

Background

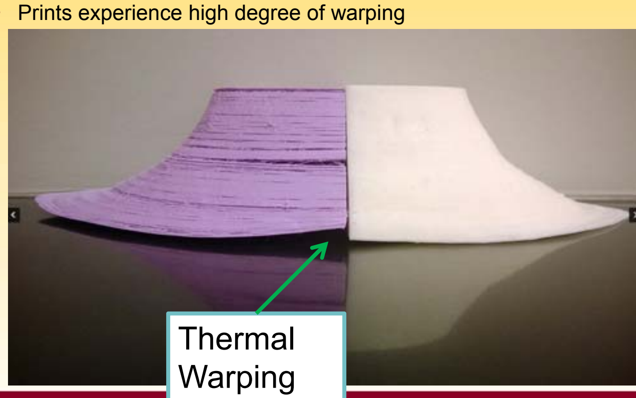
- 3D Model
  - CT of RANDO, refined with Greyscale Model Maker in 3D Slicer
- 3D Printing
  - Phantom divided into 12 parts
    - Allow for multiple film planes
    - Allow to fit in limited build volume of 3D printer



Ehler, et al. PMB 2014

Phantom Construction

- Phantom composition
  - 3D Printing solid phantom had complications
    - Print times of 12-14 hrs for 1 of 12 subsections
    - Prints experience high degree of warping



Ehler, et al.
PMB 2014

Phantom Construction

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    - Prints experienced high degree of warping
  - 3D Printed hollow phantom and filled with M3 wax

Substitute or tissue	Constituents (w/o) or formula synonyms, tradenames	Elemental composition (w/o)	SG
M3	Paraffin wax(76.92); magnesium oxide(22.35); calcium carbonate(0.72)	H(11.43); C(65.58); O(9.22); Mg(13.48); Ca(0.29)	1.05

Substitute	$(\mu/\rho)_{substitute}/(\mu/\rho)_{tissue}$					$(\mu_{en}/\rho)_{substitute}/(\mu_{en}/\rho)_{tissue}$					$(S/\rho)_{substitute}/(S/\rho)_{tissue}$					$(\bar{\Theta}^2/\rho l)_{substitute}/(\bar{\Theta}^2/\rho l)_{tissue}$
Energy (MeV)	0.01[a]	0.1	1	10	100	0.01[a]	0.1	1	10	100	0.01	0.1	1	10	100	0.01-100
M3	0.98	1.01	1.01	0.99	0.94	0.98	1.01	1.01	0.99	0.95	1.02	1.01	1.01	1.00	0.97	0.91-0.92

White D. A.
Med Phys 1978

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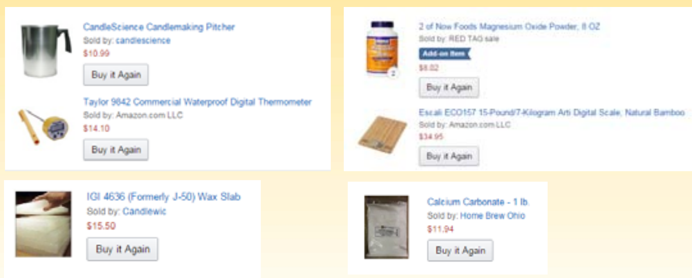
  - M3 Wax fabrication



Phantom Construction

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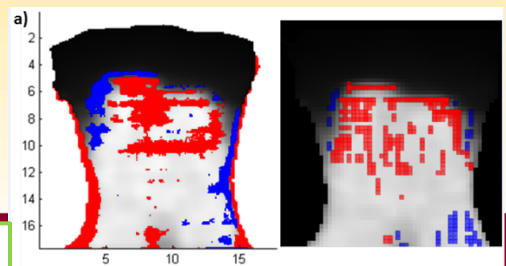
    - Prints experienced high degree of warping
  - 3D Printed hollow phantom and filled with M3 wax
  - M3 Wax fabrication
    - Weigh out wax, MgO, and $CaCO_3$
    - Place in Candle Making Pitcher
    - Place in oven in low heat (120 F)
    - Remove from oven and stir vigerously
    - Pour into hollow phantom while still stirring
    - Allow to cool (it will contract)
    - Keep pitcher heated
    - Pour additional wax on cooled wax
    - Use straight edge to smooth surface when full

3D Printed Phantoms

- IMRT test case
  - Used RANDO Phantom as the “patient”
  - Generated H&N static IMRT plan in Pinnacle
    - Allowed for low MU per Segment & small segment area to induce dose errors
  - Performed IMRT QA with Cylindrical and Planar diode arrays
    - 3D dose was reconstructed on patient volume for cylindrical phantom
  - IMRT QA also performed with 3D printed phantom
    - 3D dose reconstruction compared to 3D printed phantom dose measurements



3% no DTA comparison

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3D Printed Phantoms

- Cost
  - Total cost was about $250 USD
    - $200 for the tissue equivalent material (M3 Wax)
    - $50 for the 3D printed plastic (ABS)
- Reusable
  - M3 Wax can be reclaimed
    - M3 Wax has a much lower melting point (~100º F)
    - ABS plastic melts around (~220º F)

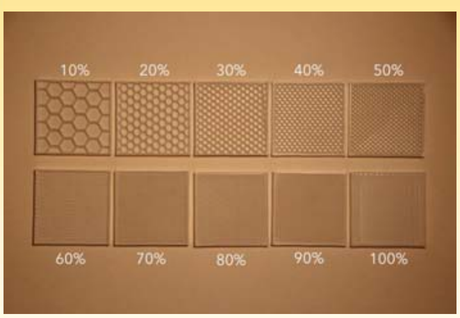
Ehler, et al.
PMB 2014

Heterogeneous Phantoms

- Most common comment about previous work
  - **What about tissue heterogeneities?**

3D Printed Phantoms

- Tissue Heterogeneities
  - Low density tissues
    - Typically elemental composition is similar to muscle
    - Change infill parameter to vary density (during slicing settings)
      - see: Feasibility of 3D printed radiological equivalent customizable tissue like materials (SU-E-T-424)



3D Printed Phantoms

- Tissue Heterogeneities
  - Low density tissues
  - High density tissues (i.e. Bone)
    - Ideally tissue density AND elemental composition would match
      - This requires new materials to be developed
    - Look at other exotic materials for 3D printing
      - Evaluated density, MVCT HU and kVCT HU

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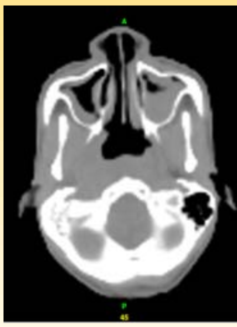
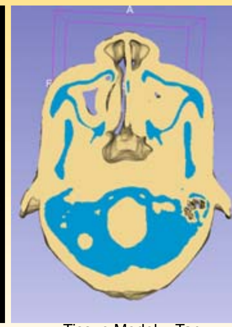
    - Look at other exotic materials for 3D printing
      - Evaluated density, MVCT HU and kVCT HU
    - PLA – Iron Composite
      - Density MVCT – 1.68 $\pm$0.09 g cm^{-3}
      - Density kVCT – 2.67 $\pm$0.17 g cm^{-3}
      - Density Measured – 1.71 $\pm$0.03 g cm^{-3}

3D Printed Phantoms

- Heterogeneous Phantom
  - Nasopharynx

Patient CT Phantom MVCT 3D Model Phantom





Tissue Model = Tan
Bone Model = Blue

PET Plastic = White
PLA-iron = Grey

3D Printed Phantoms

- Heterogeneous Phantom
  - Nasopharynx
  - Compare patient and phantom scans
    - Scan segmented into three areas:
      - Air, Soft Tissue, Bone
      - Compare densities in these regions

	Soft Tissue Density ($g\ cm^{-3}$)	Bone Density ($g\ cm^{-3}$)
Patient Scan	1.02 ± 0.08	1.39 ± 0.14
Phantom scan	1.01 ± 0.09	1.44 ± 0.12

3D Printed Phantoms

- Current Limitations
  - Long print time
    - 1 hour per millimeter for nasopharynx case
  - Limited print volume
    - Typical FDM printer build volumes around 25cm x 25cm x 25cm
  - FDM limitations
    - Plastic warping and other printing difficulties
    - Extruder nozzle leakage
      - Plastic still leaks out of high density nozzle while printing low
  - Bone tissue substitute
    - Want attenuation match over larger energy spectrum
  - Density model
    - Currently limited to bulk density correction
    - Voxel by voxel is ideal

3D Printed Phantoms

- Stereolithography
  - Most Materials have similar densities

VisiJet® M3 Materials for ProJet SD & HD Printers

The VisiJet line of plastic materials offers numerous capabilities to meet a variety of commercial applications. 3D Systems' ProJet 3500 3D printers use VisiJet M3 materials to build accurate, high-definition models and prototypes for proof of concept, functional testing, master patterns for moldmaking, and direct investment casting. Vertical markets for the ProJet 3500 line include transportation, energy, consumer products, recreation, healthcare and education. Toughness, high temperature resistance, durability, stability, watertightness, biocompatibility and castability are a few of the key attributes you will find within the VisiJet M3 materials line. Parts can be drilled, glued, painted, plated, etc. Support material offers easy, non-hazardous post-processing and preserves delicate features.

Properties	Condition	VisiJet M3-X	VisiJet M3 Black	VisiJet M3 Crystal	VisiJet M3 Proplast	VisiJet M3 Navy	VisiJet M3 Techplast	VisiJet M3 Procast	VisiJet® S300
Composition		UV Curable Plastic							Wax Support Material
Color		White	Black	Natural	Natural	Blue	Gray	Dark Blue	White
Bottle Quantity		2 kg	2 kg	2 kg	2 kg	2 kg	2 kg	2 kg	2 kg
Density @ 80 °C (liquid)	ASTM D4164	1.04 g/cm³	1.02 g/cm³	1.02 g/cm³	1.02 g/cm³	1.02 g/cm³	1.02 g/cm³	1.02 g/cm³	N/A
Tensile Strength	ASTM D638	49 MPa	35.2 MPa	42.4 MPa	26.2 MPa	20.5 MPa	22.1 MPa	32 MPa	N/A
Tensile Modulus	ASTM D638	2168 MPa	1594 MPa	1463 MPa	1108 MPa	735 MPa	866 MPa	1724 MPa	N/A
Elongation at Break	ASTM D638	8.3 %	19.7 %	6.83 %	8.97 %	8 %	6.1 %	12.3 %	N/A
Flexural Strength	ASTM D790	65 MPa	44.5 MPa	49 MPa	26.6 MPa	28.1 MPa	28.1 MPa	45 MPa	N/A
Heat Distortion Temperature @ 0.45MPa	ASTM D648	88 °C	57 °C	56 °C	46 °C	46 °C	46 °C	N/A	N/A
Ash Content		N/A	N/A	N/A	0.01 %	0.01 %	0.01 %	0.01 %	N/A
Melting Point		N/A	N/A	N/A	N/A	N/A	N/A	N/A	60 °C
Softening Point		N/A	N/A	N/A	N/A	N/A	N/A	N/A	40 °C
USP Class VI Certified*		No	No	Yes	No	No	No	No	N/A
ProJet Compatibility		SD, HD	SD, HD	SD, HD	SD, HD	SD, HD	SD, HD	HD	SD, HD
Description		ABS-like Plastic	High strength & flexibility plastic	Tough Plastic, Translucent	Plastic, Natural	Plastic, Blue	Plastic, Gray	Castable Plastic	Non-toxic wax material for hands-free melt-away supports

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3D Printed Phantoms

- Stereolithography
  - Most Materials have similar densities
    - Some higher density materials are available

VisiJet® SL Materials for ProJet 6000 & 7000 Printers

The wide range of VisiJet® SL engineered materials offers the toughest and the highest quality parts to meet a variety of commercial and production applications.

Properties	ASTM	VisiJet® SL Flex	VisiJet® SL Tough	VisiJet® SL Clear	VisiJet® SL Black	VisiJet® SL Impact	VisiJet® SL HiTemp	VisiJet® SL e-Stone™	VisiJet® SL Jewel
Composition		UV Curable Plastic							
Color		White	Gray	Clear	Black	White	Clear Amber	Peach	Blue
Cartridge Volume		2.0 liters	2.0 liters	2.0 liters	2.0 liters	2.0 liters	2.0 liters	2.0 liters	2.0 liters
Density (liquid) @ 25°C		1.14 g/cm^3	1.13 g/cm^3	1.1 g/cm^3	1.13 g/cm^3	1.12 g/cm^3	1.17 g/cm^3	1.13 g/cm^3	1.08 g/cm^3
Density (solid) @ 25°C		1.19 g/cm^3	1.19 g/cm^3	1.17 g/cm^3	1.15 g/cm^3	1.18 g/cm^3	1.23 g/cm^3	1.19 g/cm^3	1.18 g/cm^3
Tensile Strength	D 638	38 MPa	41 MPa	52 MPa	45 MPa	48 MPa	66 MPa	38 MPa	40 MPa
Tensile Modulus	D 638	1620 MPa	1890 MPa	2560 MPa	2150 MPa	2626 MPa	3390 MPa	1630 MPa	1910 MPa
Elongation at Break	D 638	16%	18%	6%	5%	14%	6%	17%	12%
Flexural Strength	D 790	57 MPa	62 MPa	83 MPa	76 MPa	74 MPa	112 MPa	57 MPa	61 MPa
Flexural Modulus	D 790	1420 MPa	1850 MPa	2330 MPa	2350 MPa	2390 MPa	3080 MPa	1550 MPa	1824 MPa
Impact Strength (Notched Izod)	D 256	22 J/m	44 J/m	46 J/m	47 J/m	65 J/m	26 J/m	22 J/m	45 J/m
Heat Distortion Temp. (HDT) @ 0.45 MPa	D 648	61 °C	62 °C	51 °C	54 °C	47 °C	65/130 °C**	61 °C	38 °C
HDT @ 1.82 MPa	D 648	53 °C	54 °C	50 °C	51 °C	42 °C	57/110 °C**	53 °C	32 °C
Hardness, Shore D		80	86	85	86	80	86	80	72
Glass Transition (Tg)	DMA, E"	60 °C	52 °C	70 °C	62 °C	65 °C	62/132 °C**	60 °C	58 °C
USP Class VI Certified*		No	No	Yes	No	No	No	No	No
ProJet Compatibility		SD, HD, MP	SD, HD, MP	SD, HD, MP	SD, HD, MP	SD, HD, MP	SD, HD, MP	MP	HD, MP

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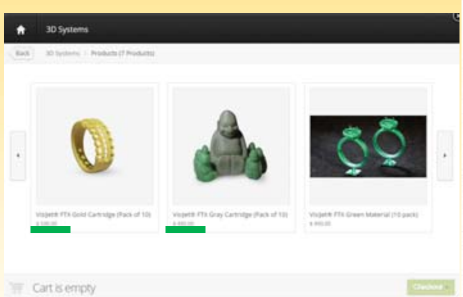
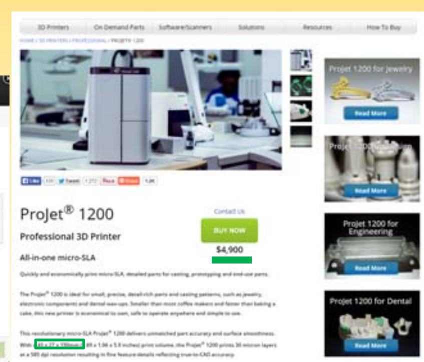
3D Printed Phantoms

- Stereolithography
  - Most Materials have similar densities
    - Some higher density materials are available
  - Cost is higher compared to FDM
    - 30 g Cartridge





43 x 27 x 150mm

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3D Printed Phantoms

- Stereolithography
  - Most Materials have similar densities
    - Some higher density materials are available
  - Cost is higher compared to FDM
    - 30 g Cartridge
    - Cost may be prohibitive compared to other phantom fabrication techniques
      - FDM most cost effective at the moment

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Thank You