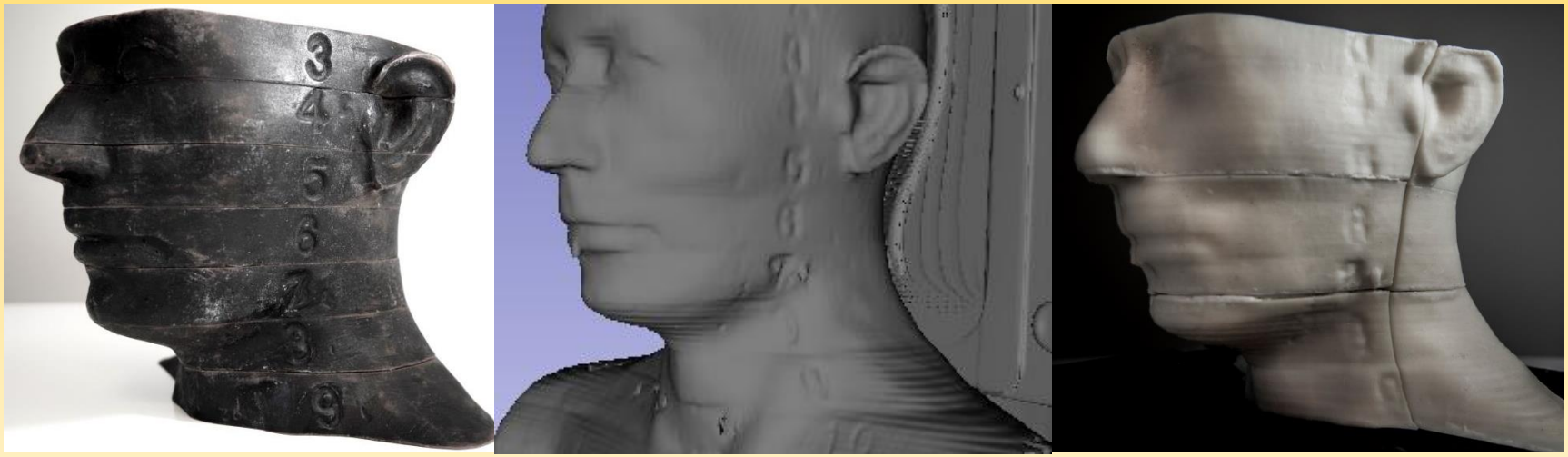
Feasibility of 3D Printed Patient-specific Phantoms for IMRT QA and Other Dosimetric Special Procedures



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What is 3D Printing?

- 3D Printing is also called Additive Manufacturing
  - Object is created by depositing successive layers of a material
  - Deposition is in the design/shape of the object
  - Object design/shape is in the form of 3D computer model
- 3D Printer is a specialized robot
  - You give it 3D computer model and build material
  - Robot builds your object
- Printing Technologies
  - Many printing technologies exist
  - Many materials available
    - Plastic, Metal, Polymers
    - Organic material

What are advantages?

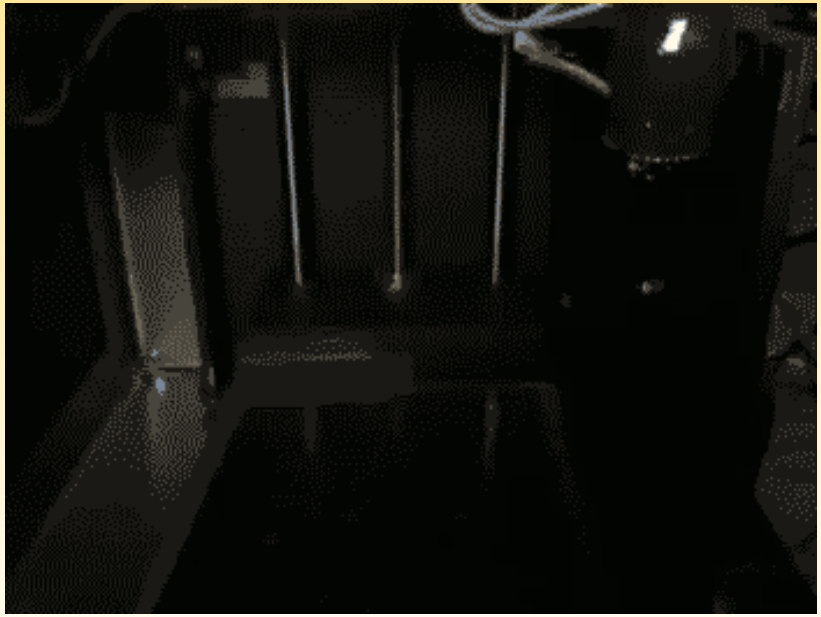
- 3D Printing is like a swiss army knife
  - Configure about anything
  - NASA will develop for space → reduce parts/tools taken to space*
- Prototyping costs lowered by factor of 10-100
  - Need only 1 of something
  - To print head replica cost $50
- Fast fabrication process
  - Have a 3D model? start printing
- Less waste than traditional methods – i.e. CNC, subtractive mfg.

- 3D Printing is inferior when you need 10,000 of same thing
  - 3D printing is good for making the mold

* Fox News 9/30/2013

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!



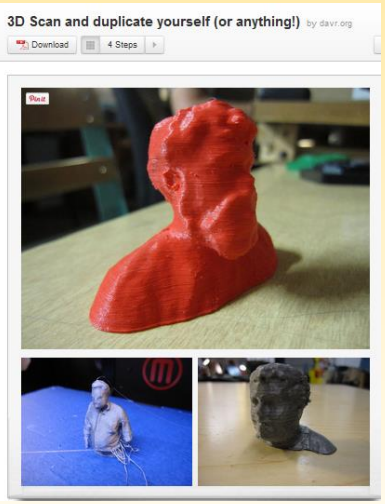
3D Printers - available

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

- Stereolithography
  - $7,000 to $600,000 for the printer
  - Material costs can be MUCH greater

Great, What do I need

- All 3D printers need a 3D Model
  - Traditionally created with Computer Aided Drafting (CAD)
  - Xbox Kinect (http://www.instructables.com/id/3D-Scan-and-duplicate-yourself-or-anything/?ALLSTEPS)
  - CT, MRI, NM + software



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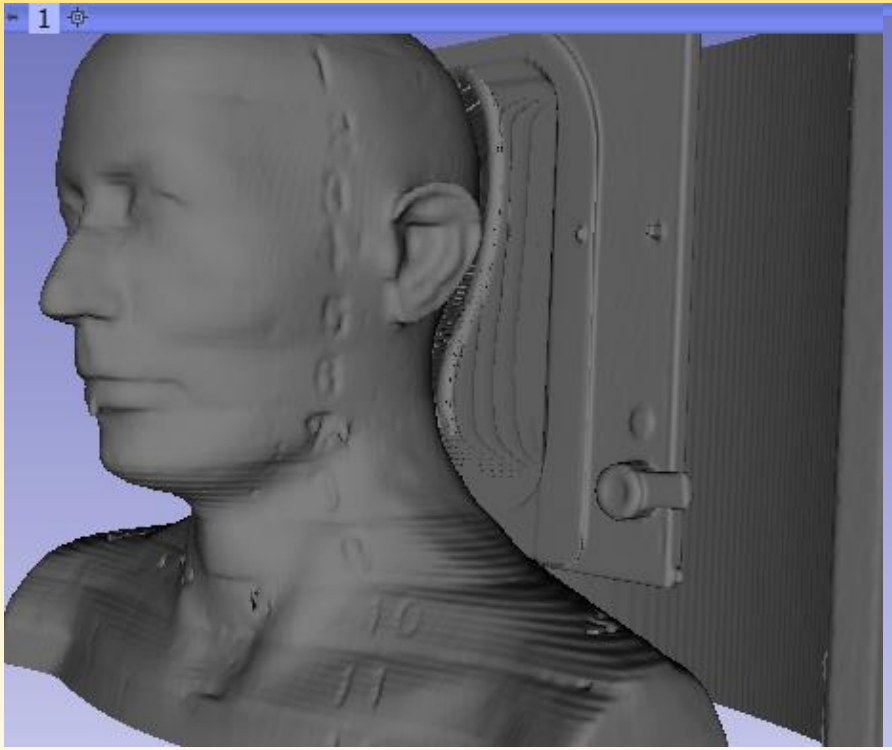
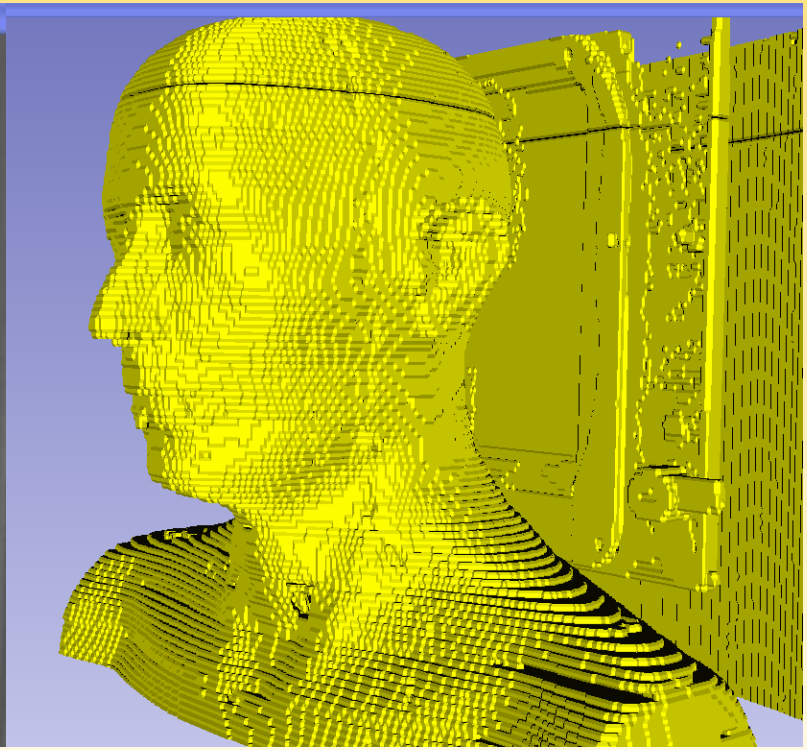


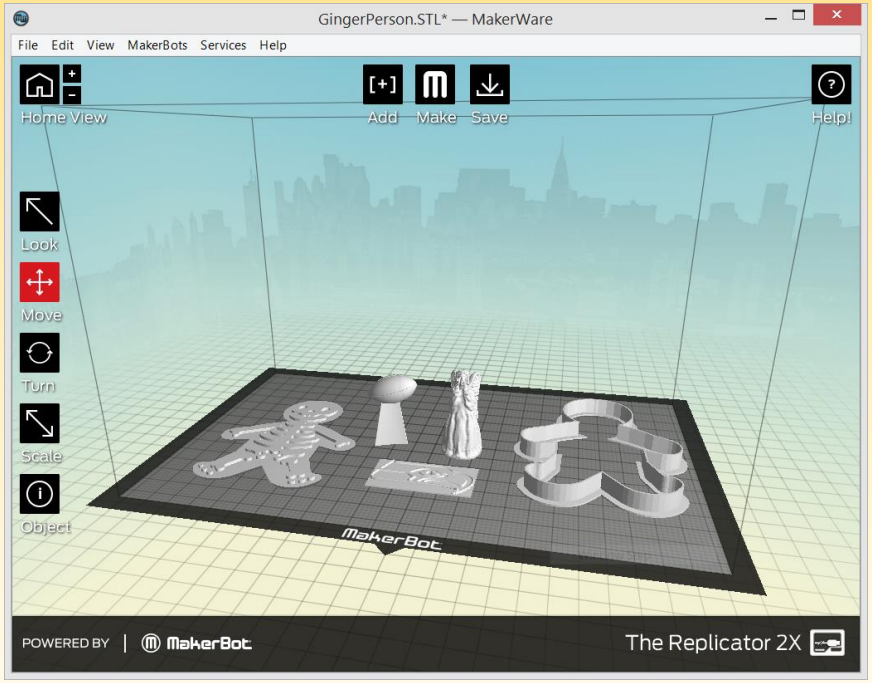


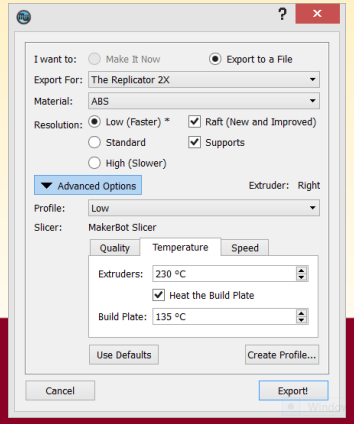
I have a 3D model, now what?

- 3D Model is converted to machine instructions
  - Robots are not yet self-aware
  - The process is call slicing
    - Converts 3D models into slice by slice 2D shapes
    - Most printers are provided with slicing software

I have a 3D model, now what?

- 3D Model is converted to machine instructions
  - The process is call slicing
- Can set machine parameters here
  - Resolution and speed
  - Material used
  - FDM
    - set extruder temperature
    - set platform temperature

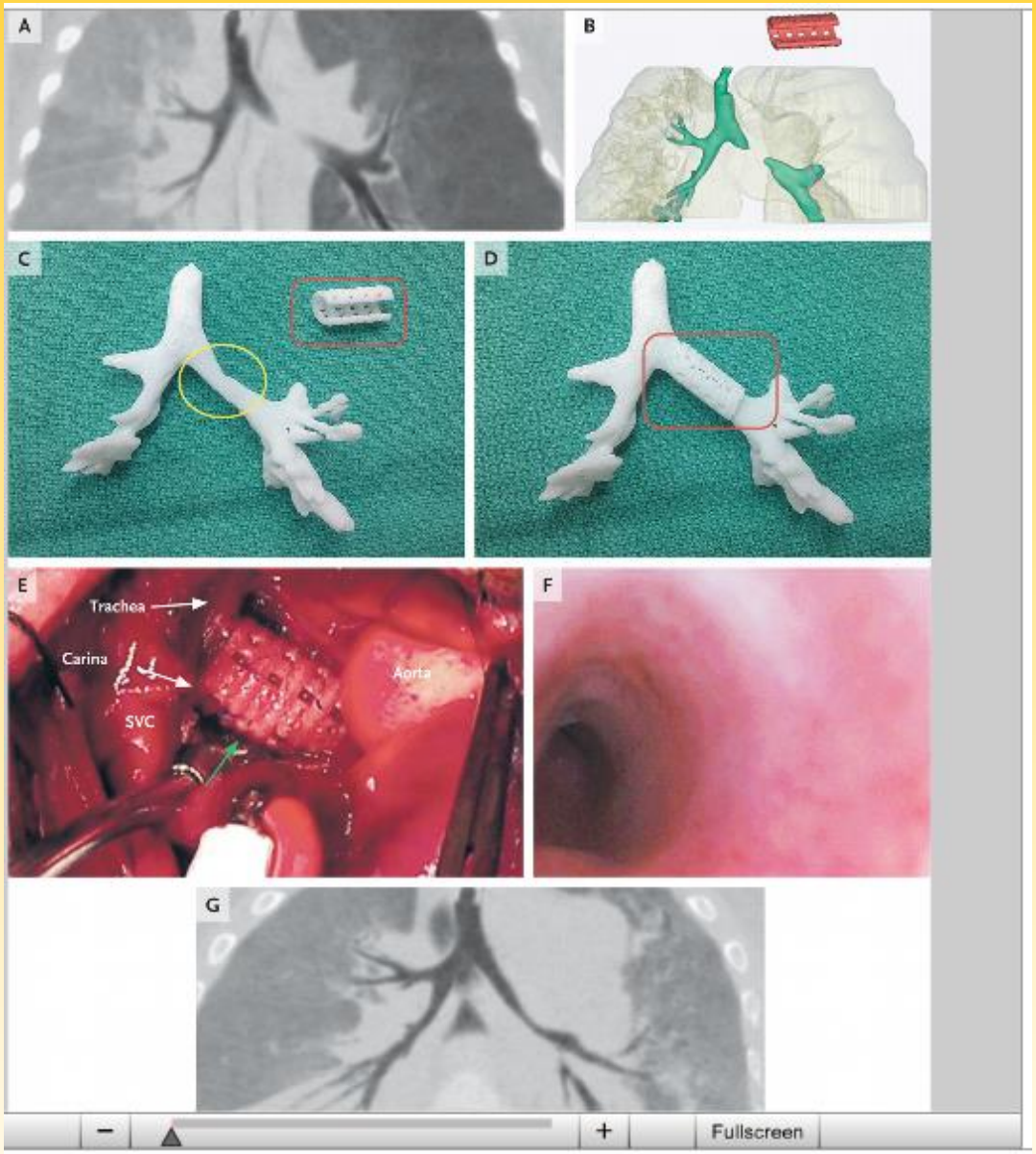




3D Printing in Medicine

- Most famous from U of Michigan
  - Create splints for collapsed airway of newborns
    - Two Reported Cases
    - Bioresorbable polyester
      - Polycaprolactone – used to fill skull after surgery
  - Use CT scan for 3D model

Hollister SJ, Green GE, Reddit IAmA, 3/18/2014
Zopf DA, Hollister SJ, et al. NEJM 2013; 368:2043-45



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3D Printing in Medicine

- Most famous from U of Michigan
  - Create splints for collapsed airway of newborns
  - Polycaprolactone – used to fill skull after surgery
- FDA clearance is an issue
  - 3D printing will be an issue for FDA
  - “the FDA has been extremely helpful”
  - “There are very few FDA approved materials for 3D-printing.”

Hollister SJ, Green GE, Reddit IAmA, 3/18/2014
Zopf DA, Hollister SJ, et al. NEJM 2013; 368:2043-45

3D Printing in Medicine

- Custom facial implants
  - Facial reconstruction after motorcycle accident
  - Titanium implants based on contralateral bones
    - Better symmetry
  - CT scan used to create 3D model
- Swansea UK
  - No idea of regulatory issues

Pioneering 3D printing reshapes patient's face in Wales
www.bbc.co.uk, 3/12/2014

3D Printing in Medicine

Stephen Power was photographed before the operation, left, and afterwards, right

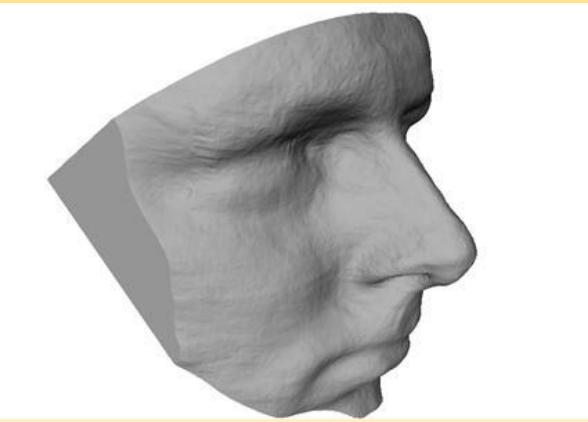
Two views of Stephen Power's skull after the operation with temporary staples

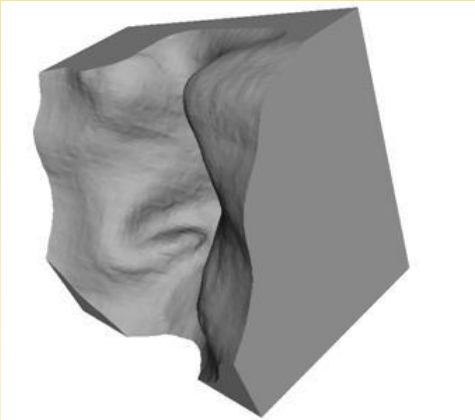
Pioneering 3D printing reshapes patient's face in Wales
www.bbc.co.uk, 3/12/2014

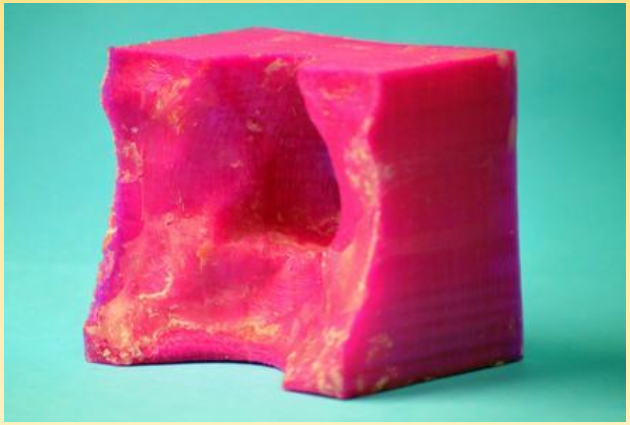
Radiation Oncology?

- Where does 3D Printing fit in Radiation Oncology?
  - Bolus is a custom fit apparatus
    - Already use thermoplastic bolus
  - Currently use universal phantoms for IMRT/IMPT QA
    - Human body is not a universal shape
    - Can we use custom form phantoms for measurements?

3D Printing for Bolus







Images courtesy of Ted Fischer

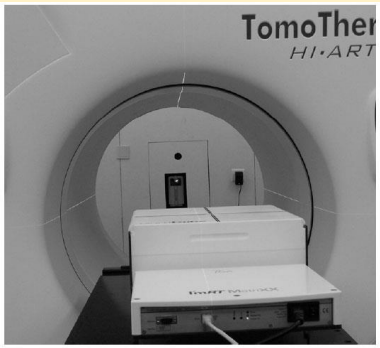
3D printed IMRT phantoms

- IMRT/IMPT QA is becoming ever more complex
- Companies specialize in phantoms
  - Recent paper found the software resulted in different pass rates*
  - How do you relate the QA result to patient treatment?
    - Can reconstruct dose on patient
    - Black box approach
    - “trust” results
      - Software defaults to give highest passing rate

*Hussein M, et al. Radiotherapy and Oncology. 2013

3D printed phantoms

- Current Detectors



(a)

(b)

3D printed phantoms

- Current Detectors
  - Have advantages/disadvantages
    - Ion chambers or diodes or film or EPID
    - Some devices have detectors at 3.3 cm depth
      - That is greater than the depth of parotid glands
      - Few monthly/annual checks of surface/buildup dose
- Evaluation largely based on Gamma Tolerance
  - Has been shown to be a bad predictor of clinical significance
  - Tolerance was established in early days of IMRT QA
- IGRT accuracy
  - Does your couch have rough or loose points?
  - How does IGRT accuracy affect your IMRT quality?

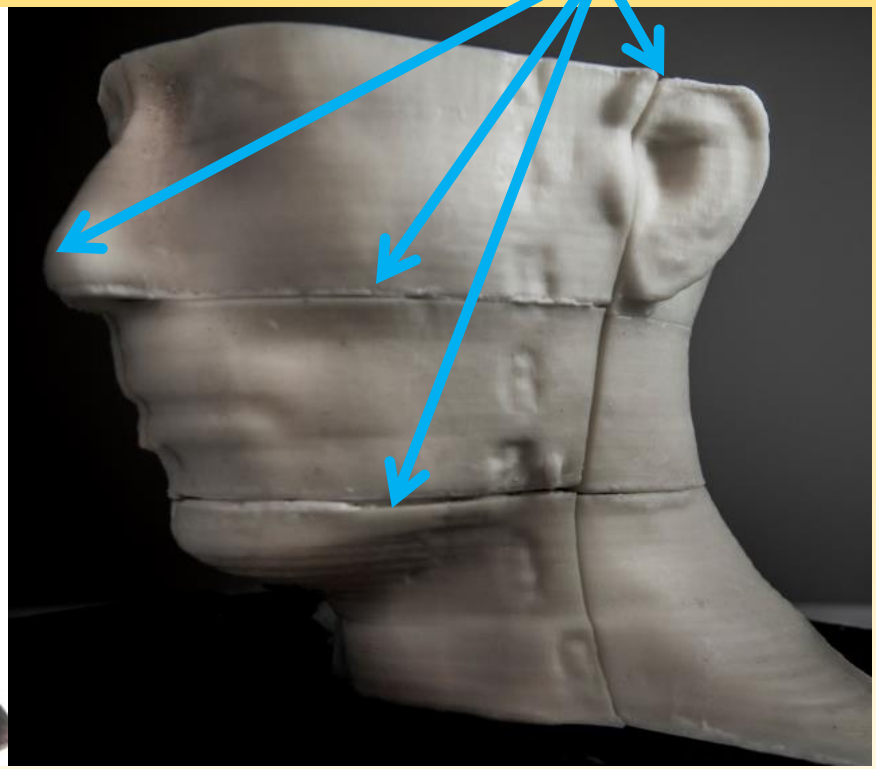
Hypothesis

- Is it practical/feasible to print the patient geometry?
  - Use RANDO phantom as “Patient”
    - Allows for dosimetry “in-vivo”
    - Avoids HIPAA
  - Follow full patient workflow

3D printed phantoms

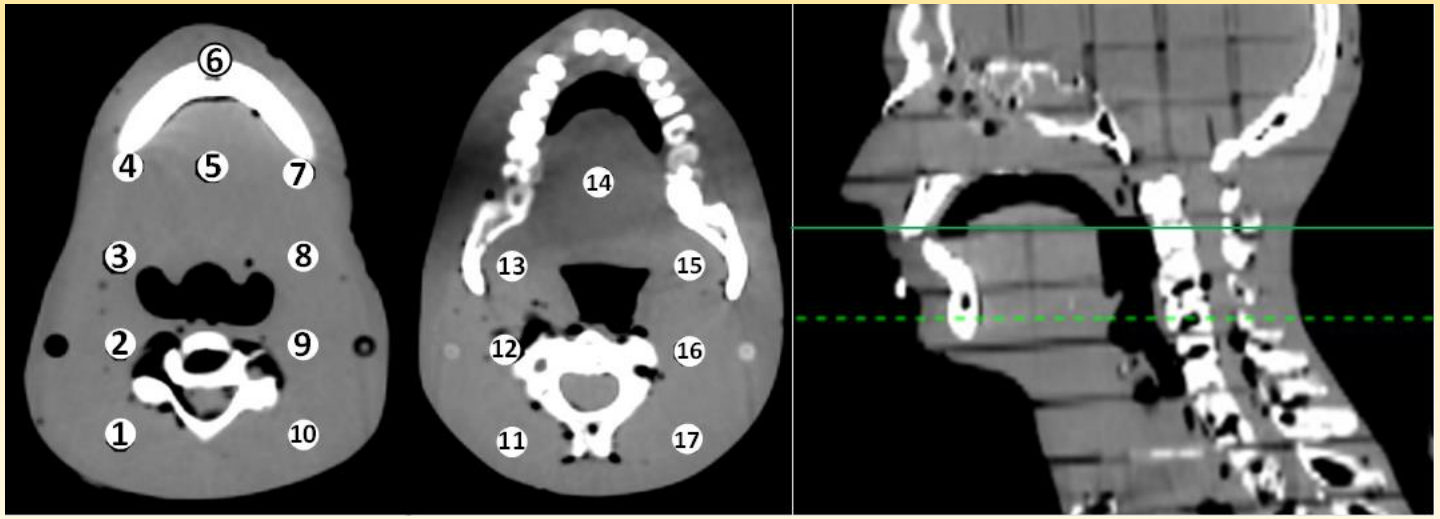
- Workflow
  - CT scan patient (CT sim)
  - Convert CT to 3D model
    - Slicer 3 – ITK from MIT/MGH
  - Insert detector points in phantom
    - Blender (open source 3D graphics software)
    - AutoCAD
    - Meshlab
    - Google Sketchup
  - Slice in Makerware
    - Whole head used $50 of ABS plastic
  - Print patient phantom
  - Fill phantom with M3 Wax

3D printed phantoms

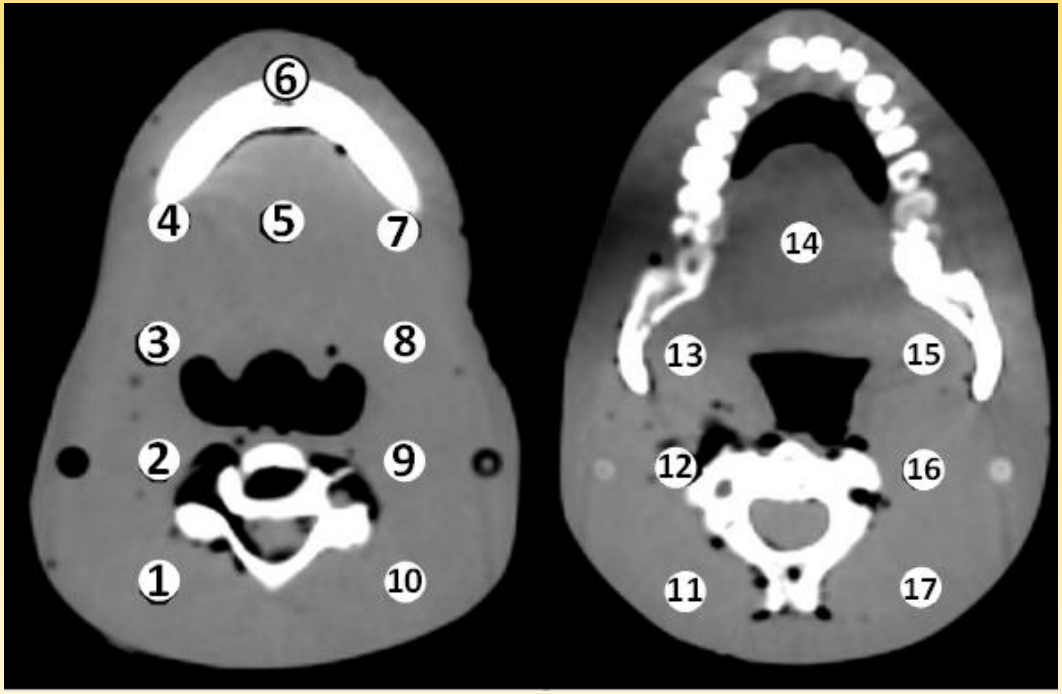


3D printed phantoms

- Test of tissue equivalence
  - How close does dose in phantom match dose in “patient”
  - Parallel opposed Head & Neck fields
  - measure dose in “patient” and in phantom



Tissue Equivalence

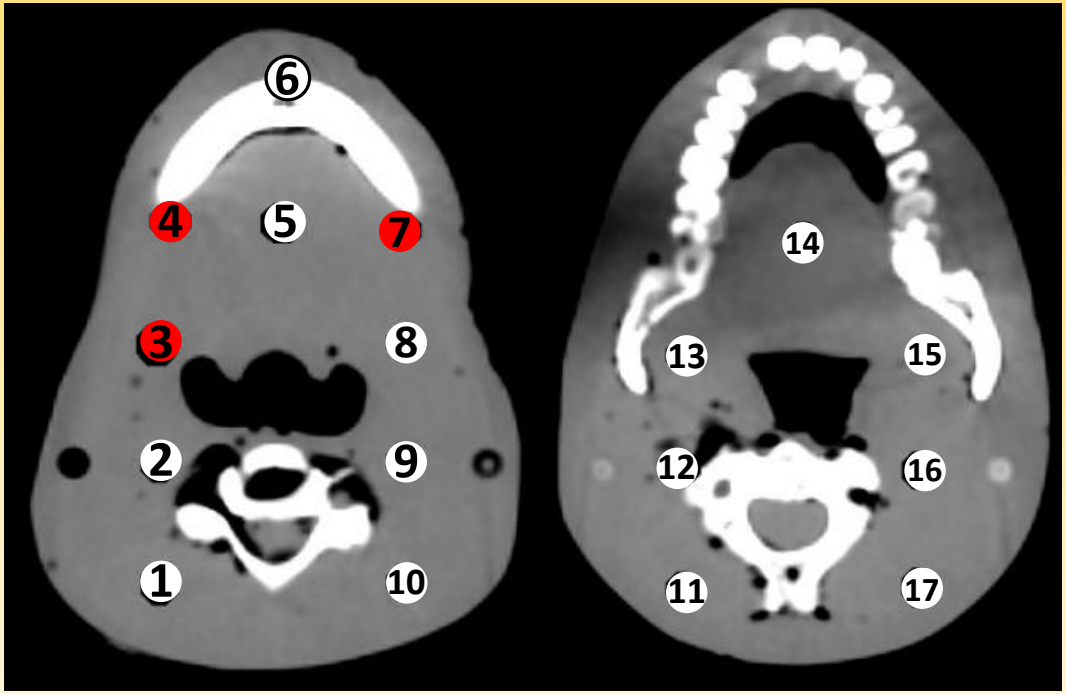


	Dose Difference	
	"Patient"	3D Printed
Region 1	0.9%	0.4%
Region 2	2.1%	1.6%
Region 3	6.8%	-3.0%
Region 4	6.8%	-4.3%
Region 5	-2.2%	-0.7%
Region 6	-0.7%	-0.7%
Region 7	4.9%	-16.4%
Region 8	3.2%	-0.6%
Region 9	1.2%	0.6%
Region 10	-2.1%	-0.3%
Region 11	5.0%	6.9%
Region 12	0.2%	0.8%
Region 13	1.2%	2.9%
Region 14	-0.8%	-1.2%
Region 15	1.3%	-1.8%
Region 16	0.7%	0.9%
Region 17	3.8%	3.3%

12 of 17 within 3%

14 of 17 within 5%

Tissue Equivalence



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Region 8	3.2%	-0.6%
Region 9	1.2%	0.6%
Region 10	-2.1%	-0.3%
Region 11	5.0%	6.9%
Region 12	0.2%	0.8%
Region 13	1.2%	2.9%
Region 14	-0.8%	-1.2%
Region 15	1.3%	-1.8%
Region 16	0.7%	0.9%
Region 17	3.8%	3.3%

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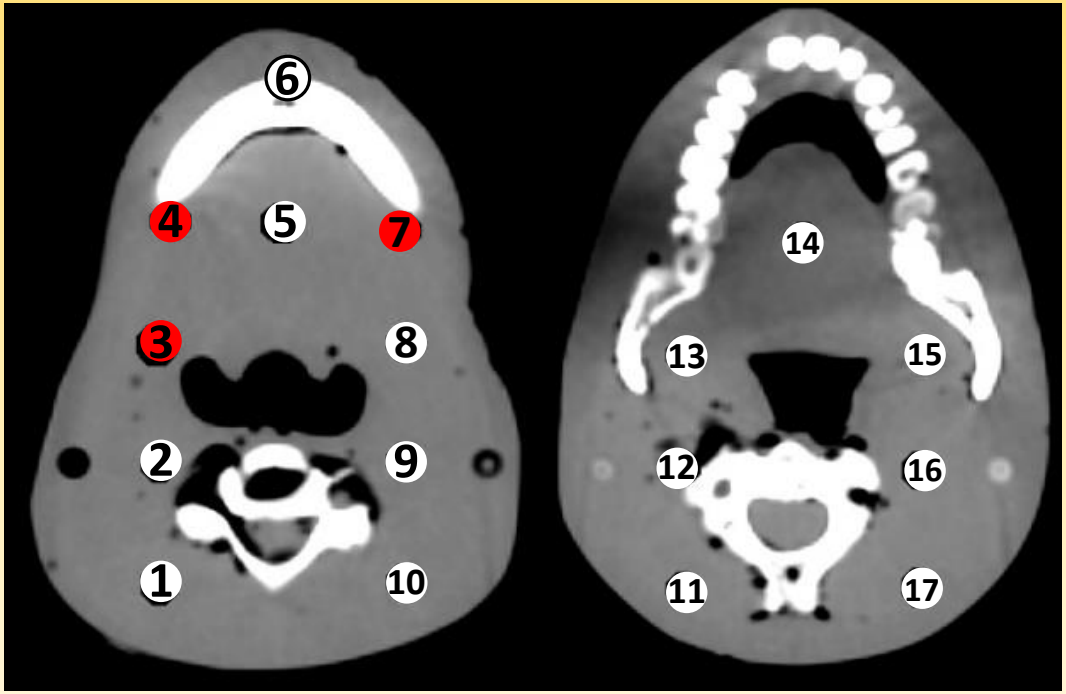

	"Patient"		3D Printed	
	Planned	Measured	Calculated	Measured
Region 1	180.6 ± 3.9	182.3 ± 3.2	181.7 ± 3.0	182.5 ± 2.3
Region 2	183.9 ± 0.1	187.7 ± 3.2	184.4 ± 0.1	187.2 ± 4.3
Region 3	182.6 ± 0.3	194.8 ± 3.3	184.2 ± 0.5	178.8 ± 1.7
Region 4	156.9 ± 15.1	169.2 ± 9.2	159.5 ± 13.6	151.7 ± 8.5
Region 5	164.8 ± 13.7	160.9 ± 9.2	165.8 ± 13.2	164.5 ± 11.2
Region 6	13.0 ± 0.9	11.8 ± 0.3	12.6 ± 1.1	11.4 ± 0.9
Region 7	171.9 ± 8.5	180.8 ± 2.5	172.8 ± 8.6	143.2 ± 13.5
Region 8	184.8 ± 0.1	190.6 ± 1.4	185.9 ± 0.4	184.9 ± 0.4
Region 9	185.2 ± 0.2	187.4 ± 2.4	186.3 ± 0.1	187.4 ± 2.3
Region 10	183.4 ± 2.1	179.7 ± 2.6	184.3 ± 1.8	183.7 ± 1.1
Region 11	163.4 ± 14.0	172.4 ± 7.7	166.6 ± 12.2	179 ± 6.6
Region 12	179.5 ± 0.2	179.9 ± 0.9	180.2 ± 0.3	181.6 ± 2.0
Region 13	173.7 ± 1.1	175.9 ± 0.9	174.2 ± 1.4	179.4 ± 3.3
Region 14	14.8 ± 0.6	13.3 ± 0.4	14.5 ± 0.6	12.4 ± 0.6
Region 15	174.9 ± 1.3	177.3 ± 2.0	175.7 ± 1.7	172.5 ± 1.2
Region 16	180.9 ± 0.4	182.1 ± 0.6	181.9 ± 0.4	183.5 ± 2.2
Region 17	167.1 ± 14.7	175.1 ± 6.2	169.2 ± 13.4	175.1 ± 6.2

12 of 17 within 3%

14 of 17 within 5%

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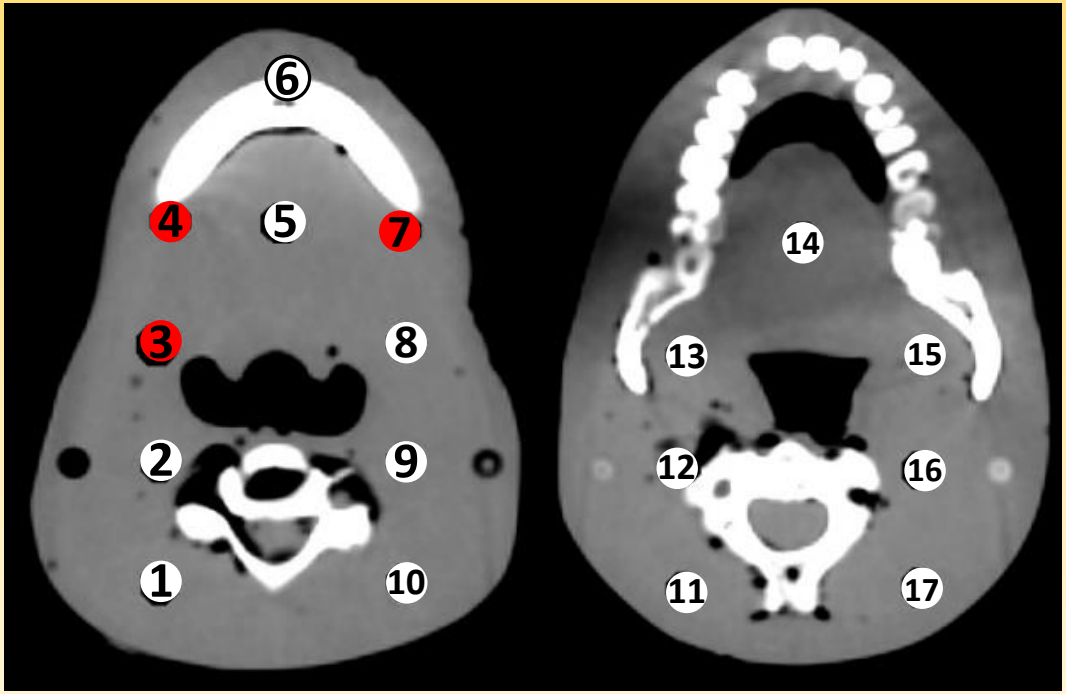

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12 of 17 within 3%

14 of 17 within 5%

Comparison of IMRT QA Results

- Perform QA on Printed phantom
  - Compare to cylindrical and planar IMRT QA measurement
  - Dose reconstruction algorithm with cylindrical data
    - Cylindrical measurements → reconstruct dose on patient
    - Software allows recalculation of DVH

Comparison of IMRT QA Results

- Cylindrical and Planar QA
  - Passing Rates (Default Settings)

	3 mm / 3%	3%	5%
Cylindrical	99.7%	94.4%	98.0%
Planar 1	99.1%	88.1%	97.0%
Planar 2	99.3%	89.3%	94.2%
Planar 3	100.0%	90.1%	96.5%
Planar 4	98.7%	88.9%	94.9%
Planar 5	100.0%	84.4%	94.8%
Planar 6	99.7%	87.8%	94.0%
Planar 7	99.6%	89.3%	96.3%
Planar 8	98.6%	88.1%	93.2%
Planar 9	99.6%	90.4%	95.6%

Comparison of IMRT QA Results

- Cylindrical and Planar QA
  - Passing Rates

	3 mm / 3%	3%	5%
Cylindrical	95.9%	69.2%	80.4%
Planar 1	92.4%	61.3%	69.7%
Planar 2	93.5%	68.7%	74.6%
Planar 3	96.2%	67.2%	71.8%
Planar 4	94.4%	65.1%	72.4%
Planar 5	96.5%	69.4%	75.4%
Planar 6	95.5%	66.6%	74.4%
Planar 7	93.7%	63.4%	75.0%
Planar 8	89.1%	63.3%	69.4%
Planar 9	93.4%	63.5%	70.4%

Comparison of IMRT QA Results

- Cylindrical and Planar QA

	3 mm / 3%	3%	5%
Cylindrical	95.9%	69.2%	80.4%

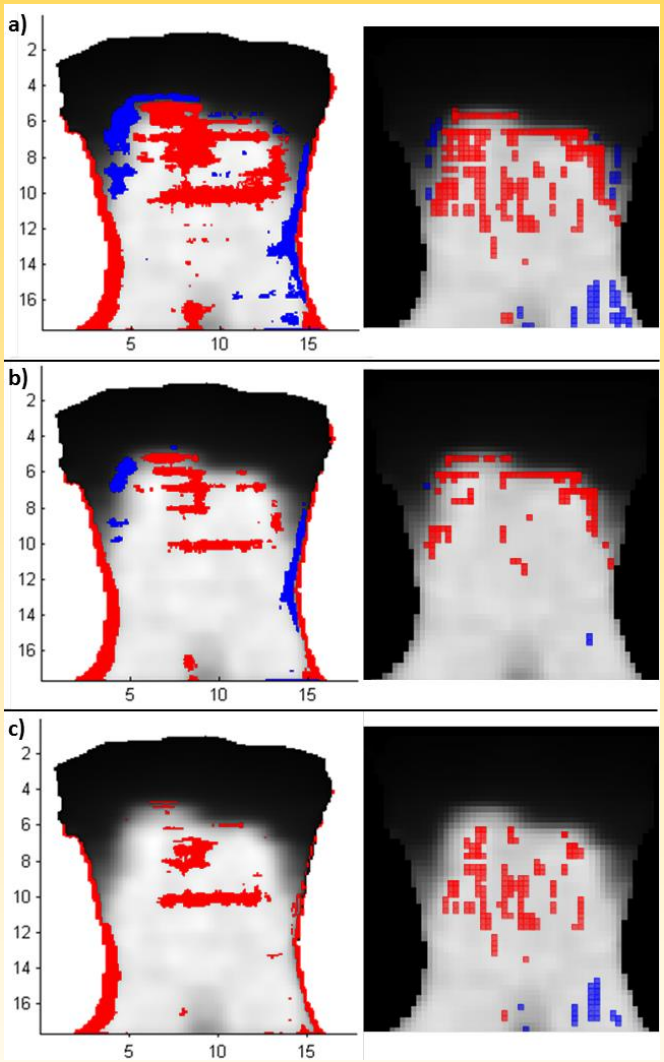
- Dose Reconstruction Results

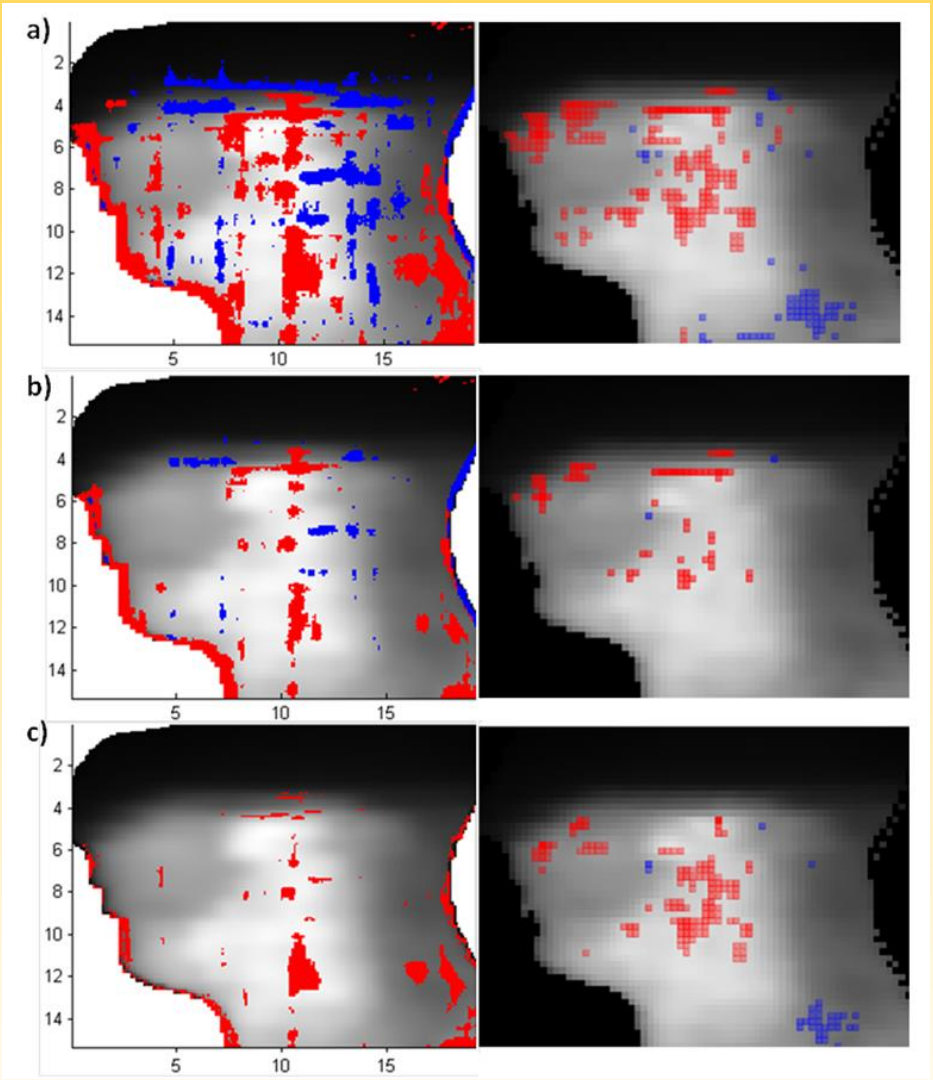
	3 mm / 3%	3%	5%
Superior Axial	95.3%	74.5%	90.3%
Inferior Axial	96.7%	92.8%	99.5%
Coronal	95.7%	89.0%	96.1%
Sagittal	96.1%	90.8%	97.9%

- 3D Printed Phantom Results

	3 mm / 3%	3%	5%
Superior Axial	87.0%	63.2%	80.9%
Inferior Axial	91.6%	67.0%	82.8%
Coronal	91.8%	73.5%	85.7%
Sagittal	94.6%	75.0%	90.9%

Comparison of IMRT QA Results





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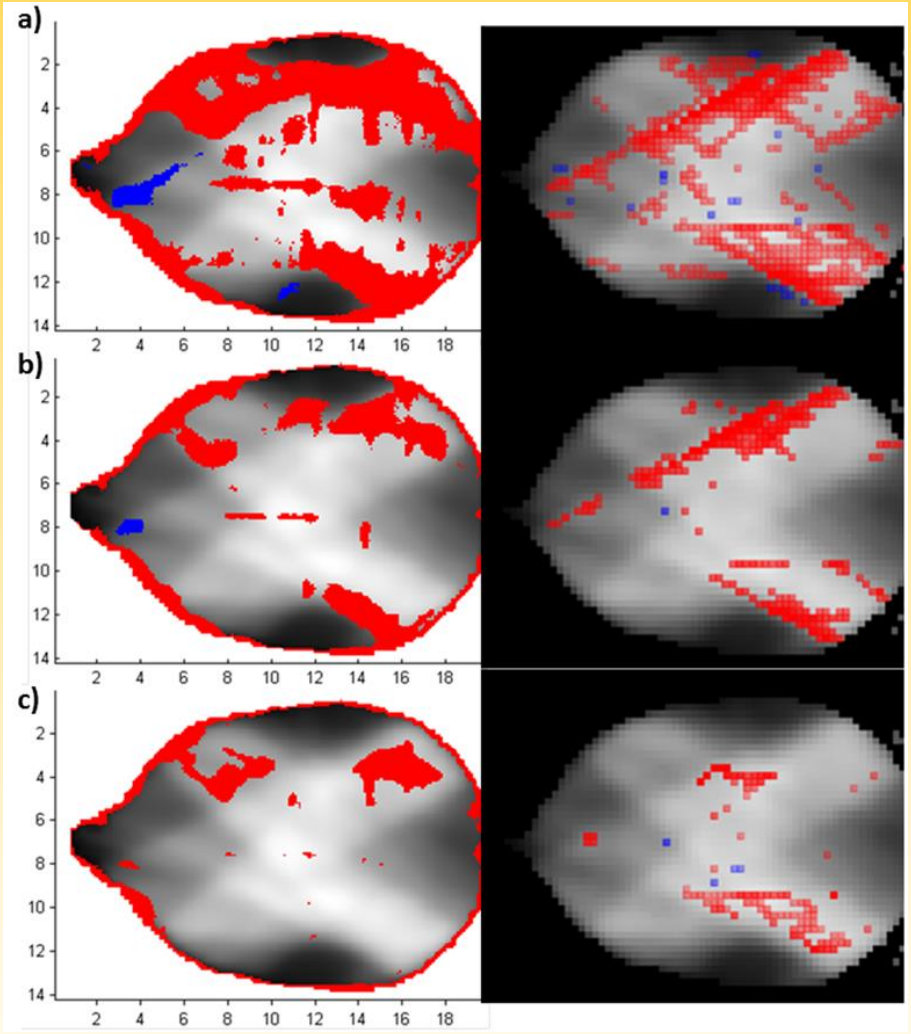
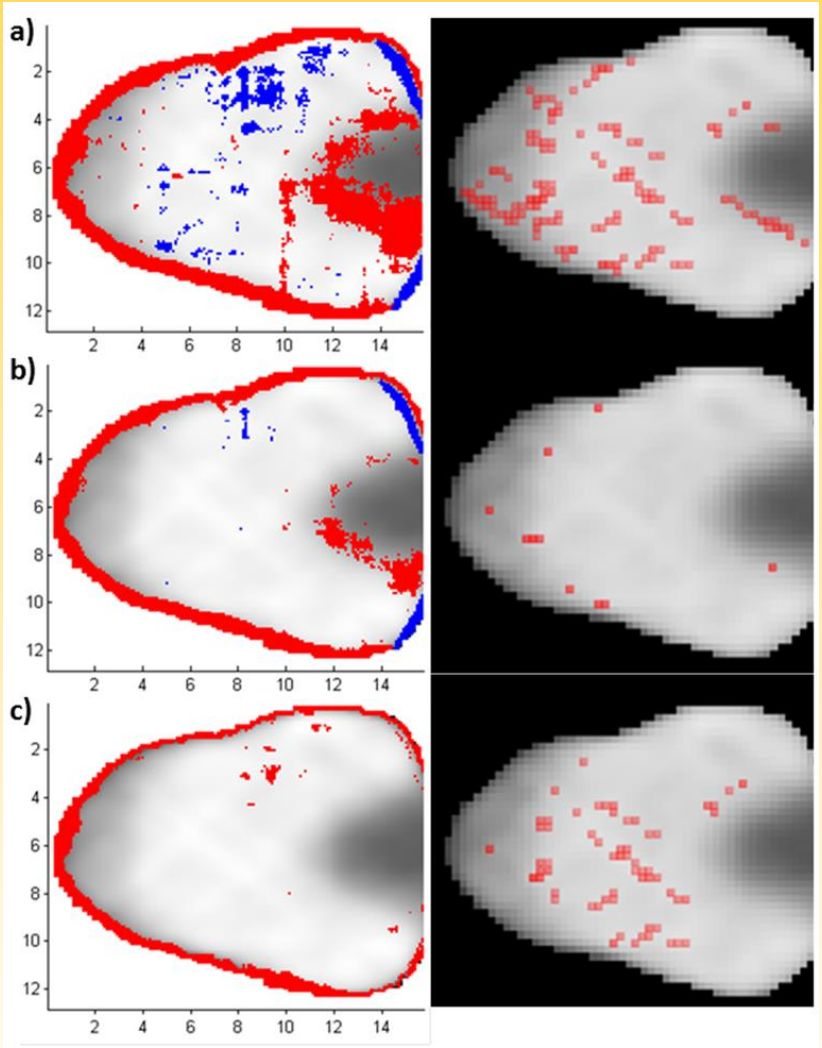


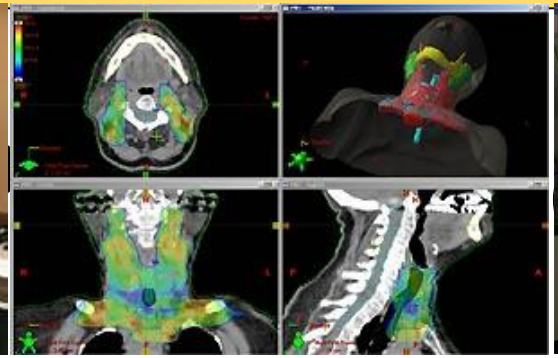


Comparison of IMRT QA Results

- Dose Reconstruction assumes perfect beam model
  - No beam model is perfect!
    - Isn't that why we do the IMRT QA in the first place?
  - In this case, observe disagreement at superficial depth
    - Detector depth 3.3 cm
  - 3D printed phantom show effect of couch, head frame, etc.

- 3D printed phantom → end-to-end test
  - Similar workflow as patient
  - CT, Dose, position, IGRT, IMRT

Work flow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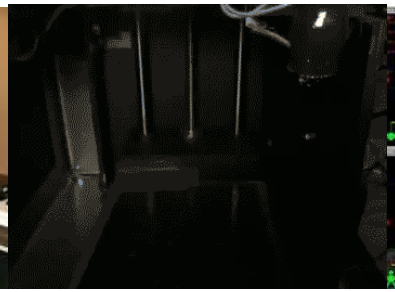
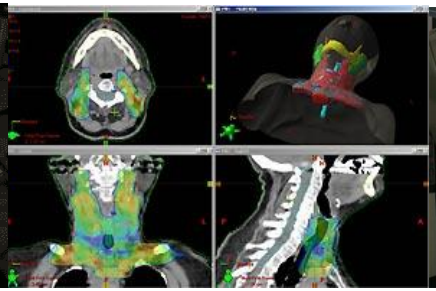
Millennium MLC: Clinac® EX with MLC-120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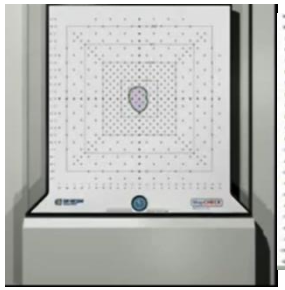
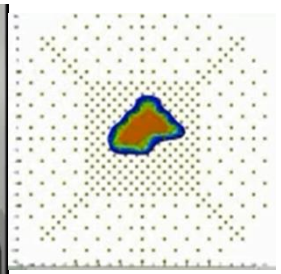
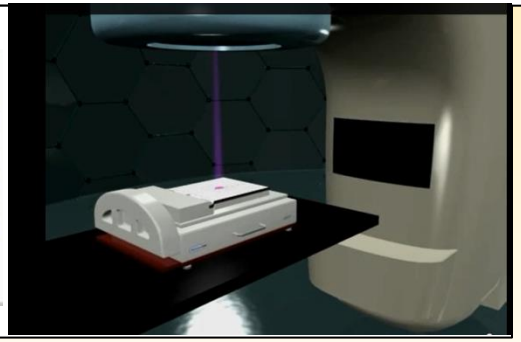
Millennium MLC: Clinac® EX with MLC-120

Conclusions

- 3D Printed IMRT QA Phantom is an End-to-End Test
  - IMRT Commissioning quality measurements on per-patient basis
    - Include couch, frame, etc. transmission
  - Include IGRT accuracy in dosimetric assessment
  - Test much more links in the treatment chain
    - Not just test MLC / Beam Quality
  - Clinically Relevant Dosimetric Results
  - Not software driven but dosimeter driven Quality Assurance
  - Tailor measurements as needed for specific case
  - Cost:
    - $1000s for printer
    - $50 for plastic
    - $150 for M3 wax (reusable)

That is 3D Printing in IMRT QA

Are you pumped up for 3D Printing?