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3D Printed Phantoms for Small Field Dosimetry Applications

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Background

- End to end test of GK Perfexion
  - Lack of test object / phantom for the Leksell G frame and imaging fiducial systems (CT and MRI)
  - RPC and commercial phantoms check dosimetry but not accuracy of fiducials
  - Elekta performs QA on G frame only annually
- Small animal irradiation
  - Accuracy of dose delivery on linear accelerator

Abstract

- 3D scanning and printing technology is utilized to create phantom models in order to assess the accuracy of ionizing radiation dosing for two scenarios involving small field dosimetry.
- Firstly, an end to end test of the Gamma Knife Perfexion system is performed.
- Secondly phantoms are designed to simulate a range of research questions including irradiation of lung tumors and primary subcutaneous or orthotopic tumors for immunotherapy experimentation in mice. The mouse phantoms are used to measure the accuracy of dose delivery and then refine it to within 1% of the prescribed dose.

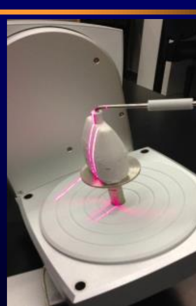
3D printing resources

- Dedicated biomedical engineering laboratory
  - UC Davis has BME department
- Nextengine 2020i laser scanner
  - Digitizes 3D object, creating map
- Netfabb v. 5.0 software and Autodesk Inventor Professional 2014 software
  - 3D computer aided design (CAD)
- Objet 260 Eden printer – prints clear, opaque and rubber

3D printing resources cont.

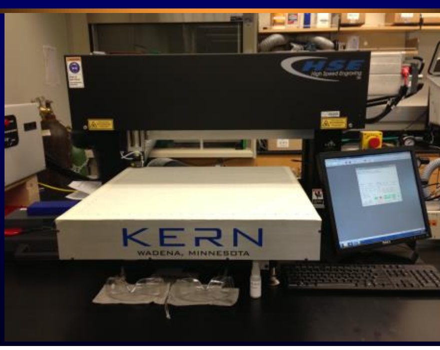
- VeroClear photo-polymer
  - 16µm layers, with each layer hardened by ultraviolet light. Stated accuracy of the print is 20 – 85 µm for features below 50mm and 200µm for the entire printed object
- Kern Electronics Micro 24, 190W CO_2 Laser Cutter

3D laser scanner



3D Objet 260 printer

Kern Electronics laser cutter



Gamma Knife Perfexion QA

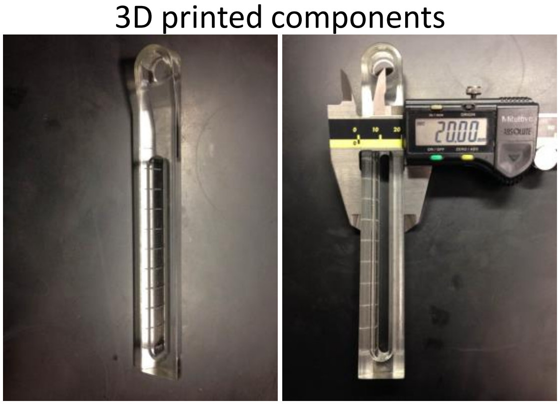
- End to end test for MRI based treatment
- To test MRI the phantom must have predefined stereotactic coordinates
- Stereotactic frame must attach to phantom with sub-millimeter precision
- MRI compatible markers at predefined Leksell coordinates

Printing G frame – proof of principle

- Confirm accuracy of laser scanning and printing
- Created duplicate G frame
  - Laser scanning
  - 3D printing
- Caliper measurements to compare printed to original
  - Dimensions measured to within 0.01mm
- Confirmation by fit into GK Perfexion unit

Original G frame component

3D printed components



Gamma Knife Phantom Process

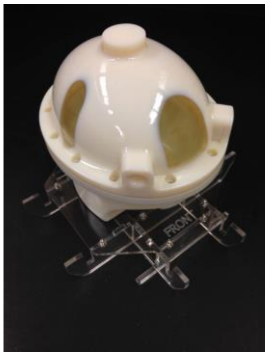
- Built MR fiducial system in CAD software to be mounted on G frame (virtual)
- Designed head shaped phantom
  - Water filled
  - Reduced weight by removing chin
  - Two halves to allow printing shell
- Replaceable marker balls serve as stereotactic coordinates
- Phantom includes detector chamber hole and film holder

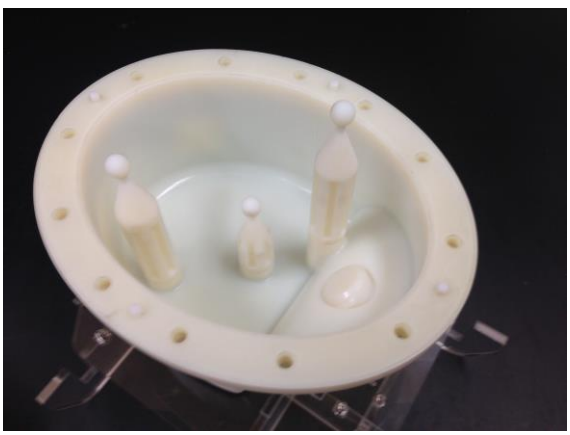
Replaceable pin mounting sites (pads) and screw in marker balls

Mounting plate

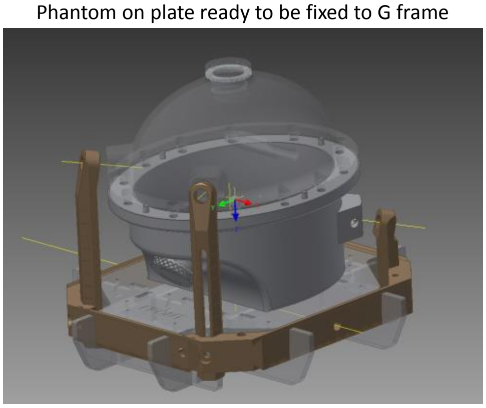
- Needed to fix spatial relationship between G frame and phantom
  - Fitting to human patient has spatial variability
  - Mounting plate fixes variability
  - Reproducible
  - Built Leksell coordinate system in CAD software, which means exact distances for marker ball to mounting plate

Printed Phantom on laser cut mounting plate

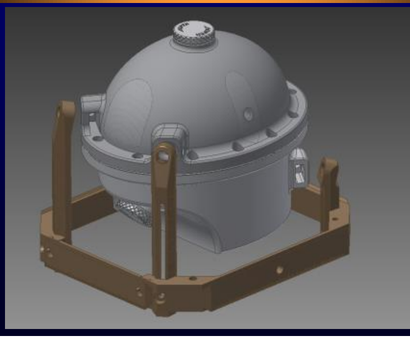




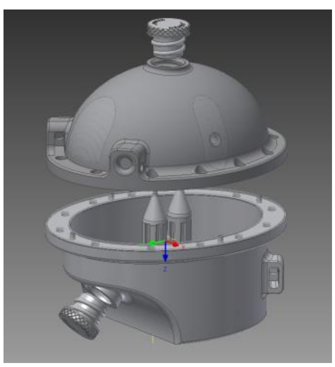
Phantom on plate ready to be fixed to G frame

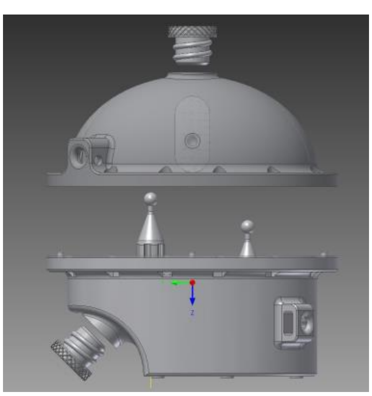


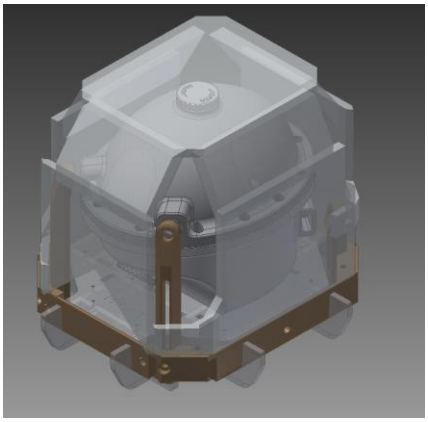
Phantom in frame lifted off mounting plate ready for MR or treatment

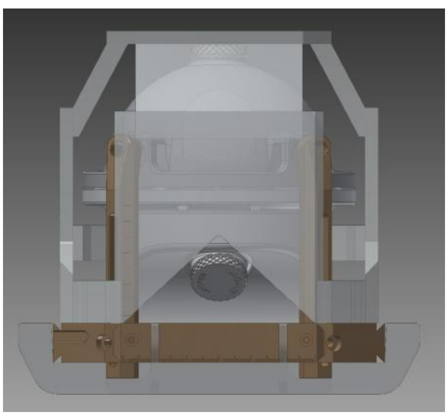


X,Y,Z coordinate system matches Leksell planning system

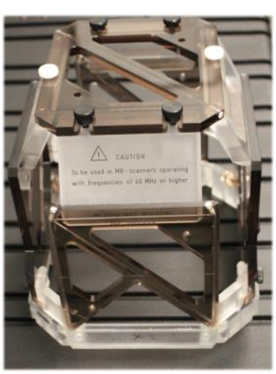








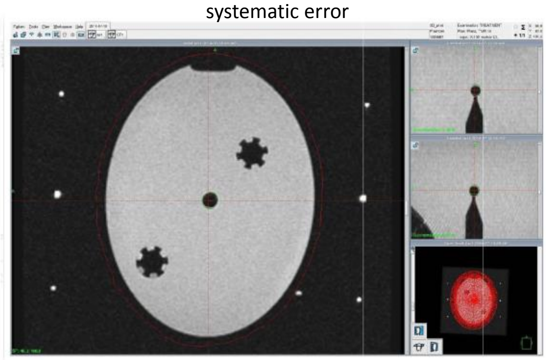
Leksell MRI fiducial box attached to printed G frame



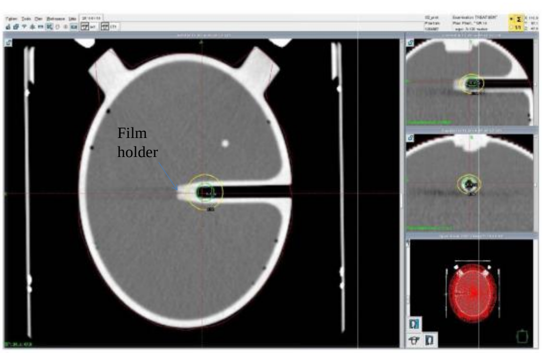
Details of image acquisation

- CT – GE lightspeed big bore
  - 2mm slice thickness, helical SRS brain protocol
- MR – GE Signa 1.5T
  - 2mm slice thickness, Gamma Knife T1 axial protocol

Screen capture CT contour on MR scan to assess systematic error



CT scan of printed phantom with dose distribution



Gamma Knife Phantom Results – Leksell coordinates in mm

	MRI		CT		Difference (MR - CT)	Planned	
100 marker	x	100.1	x	100	0.1	x	100
	y	97.7	y	98.4	-0.7	y	100
	z	100.2	z	100.8	-0.6	z	100
140 marker	x	66.2	x	66.5	-0.3	x	65
	y	57.4	y	58.3	-0.9	y	60
	z	60.8	z	60.8	0	z	60
160 marker	x	125.3	x	125.6	-0.3	x	125
	y	126.5	y	127.2	-0.7	y	130
	z	41.2	z	41.5	-0.3	z	40

Gamma Knife Phantom Results - Positioning

- Position of marker balls
- Less than 1mm difference between MR and CT for the center of the marker
- Approximately 2mm shift of marker ball posteriorly along y axis
- Further investigation underway on reproducibility – suspect shift introduced tightening pins

Gamma Knife Phantom Results - Dosimetry

- Absolute dosimetry with ion chamber
- Dose measurement
  - Mean dose to chamber contour in planning system – 5.90Gy
  - Measured dose, calibrated A1SL chamber, Max4000 electrometer – 5.94Gy
  - 0.7% difference
- Further investigation will measure spatial dosimetry with radiochromic film

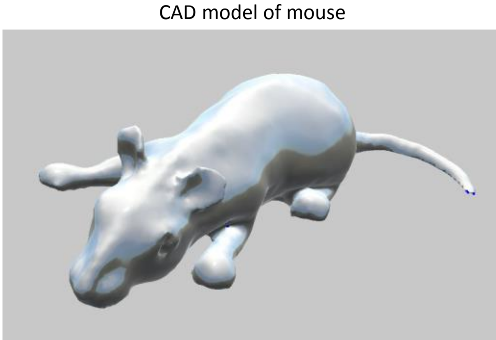
Small animal irradiation

- Radiation oncology department serves 8 investigators with small animal irradiations
- Linear accelerator for human use
- Special calculations for small field applications
- Question of accuracy of dose prescription to small animal

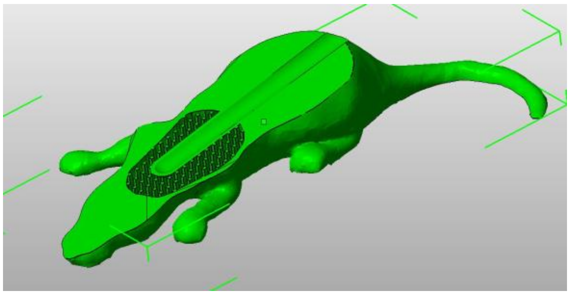
Small Animal Printing Process

- 3D scan of toy mouse
- CAD model adjusted for each scenario
  - Whole body irradiation
  - Lung model
  - Bilateral flank tumors
- Printed mice adjusted to accommodate A1SL or MOSFET detectors

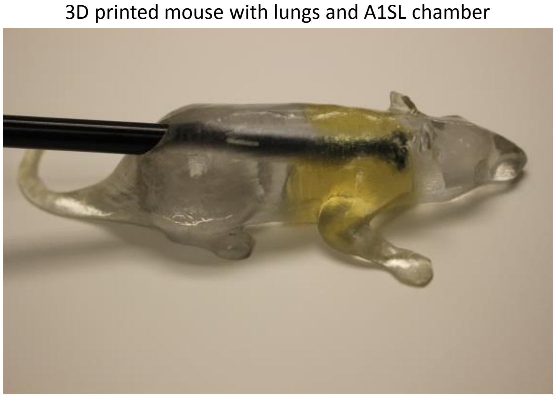
CAD model of mouse



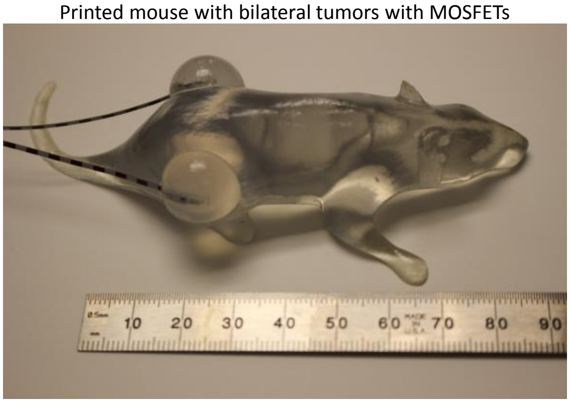
CAD model with lungs – bulk approach to density correction by removing 2/3 printed material



3D printed mouse with lungs and A1SL chamber



Printed mouse with bilateral tumors with MOSFETs



Comparison 3D printed to real mouse – electron density

Scanned area	Density g/cm³
Solid water	1.06
Bolus material (superflab)	1.00
Phantom mouse material	1.15
Phantom mouse (lung)	1.06
Mouse gut	1.12
Mouse lung	0.66
Mouse bone	1.21

Mouse Dosimetry Results

Setup of Phantom Irradiation	Energy	Prescribed dose / monitor units	Measured dose / Gy	Comments
Whole body, 1cm bolus directly on mouse	6MV X-rays	2Gy / 191MU	2.001	
Whole body in cage, 1cm bolus material draped over cage	6MV X-rays	2Gy / 191MU	1.968	1.7% lower due to loss indirect bolus
Mouse gut, 1cm bolus, half blocked field	6MV X-rays	2Gy / 203MU	2.003	Average measured dose from three positions
Mouse lung, solid mouse, 1cm bolus, 3x3cm field size	9MeV electrons	2Gy / 227MU	1.958	2.1% lower than prescribed
Mouse lung, solid mouse, 1cm bolus, 3x3cm field size	9MeV electrons	2Gy / 223MU	2.001	Monitor units adjusted

Summary and Conclusion

- Demonstrate ability to create and model GK components with sub mm accuracy
- Printing options for wide range of detectors
- Mouse model allows validation of new research protocols