Development of an anthropomorphic head phantom for the assessment of proton therapy treatment procedures

Paige Summers, David Followill, Narayan Sahoo, Falk Pönisch, Susan Tucker, Michael Gillin, Beverly Riley, & Geoffrey Ibbott

Department of Radiation Physics
The University of Texas, M.D. Anderson Cancer Center, Houston, TX 77030

Purpose: This study sought to develop a head phantom for the Radiological Physics Center (RPC), to be used for credentialing of institutions wishing to participate in clinical trials involving proton therapy. This phantom is one of the first designed at the RPC for proton therapy credentialing and in the assessment of proton therapy facilities.

Proton therapy has become an increasingly more common method of radiation therapy, with the dose sparing to distal tissue making it an appealing option, particularly for treatment of brain tumors [1, 2]. As there is much variability in the make, model, and maintenance of proton therapy facilities, it is imperative to ensure the treatment procedures at each institution are accurate and comparable. Phantom audits are a way of testing a facility's treatment process from start to finish: treatment simulation, treatment planning, and treatment delivery. We developed a head phantom that improves upon previous phantom models by using materials that better match human anatomy based on the stopping power-Hounsfield unit (HU) calibration curve that is used by proton treatment planning software.

Materials/Methods: The phantom was designed using a solid Alderson material cast around a human skull. The Alderson material has stopping power and HU values very near to water (relative stopping power: 1.00, HU: 16 ± 5), which is approximately tissue equivalent. The HU-RSP curve used with various phantom materials included is shown in **Figure 1.**

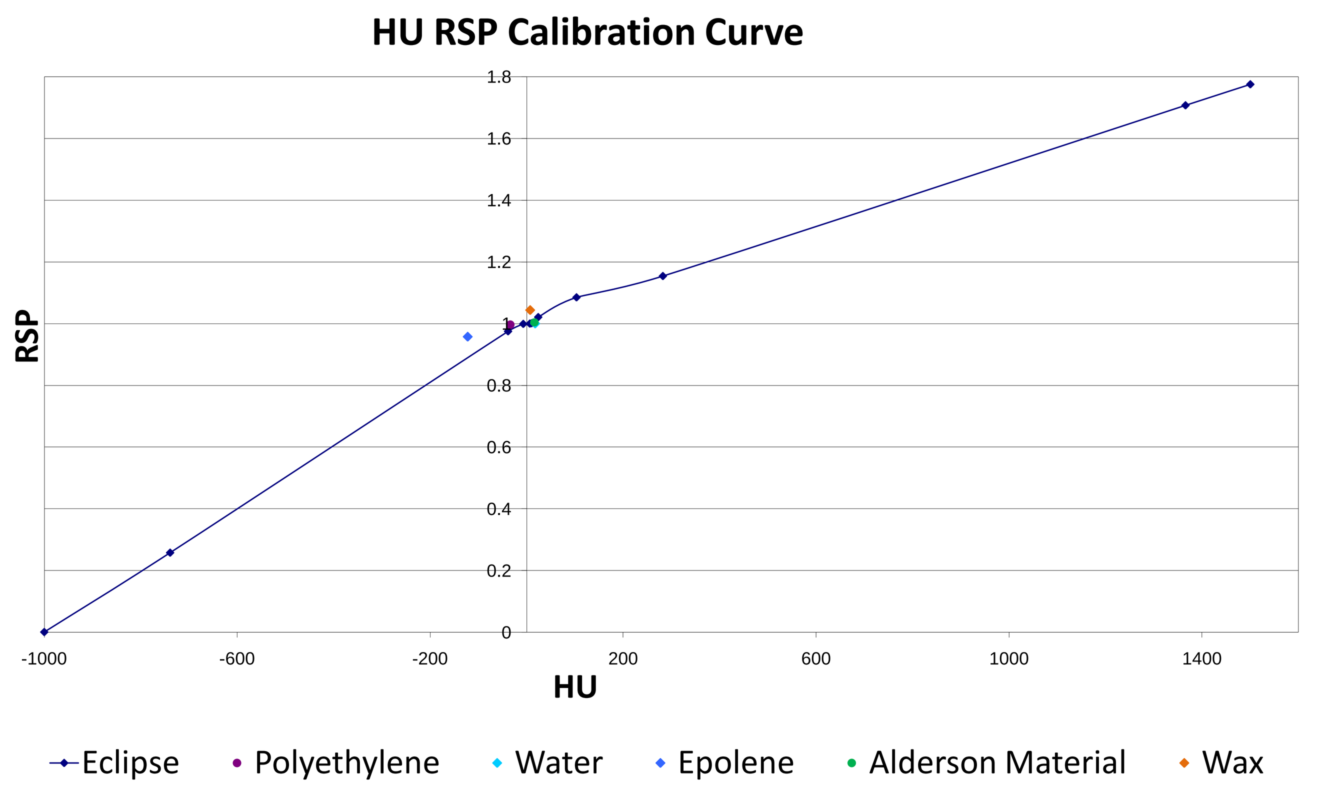


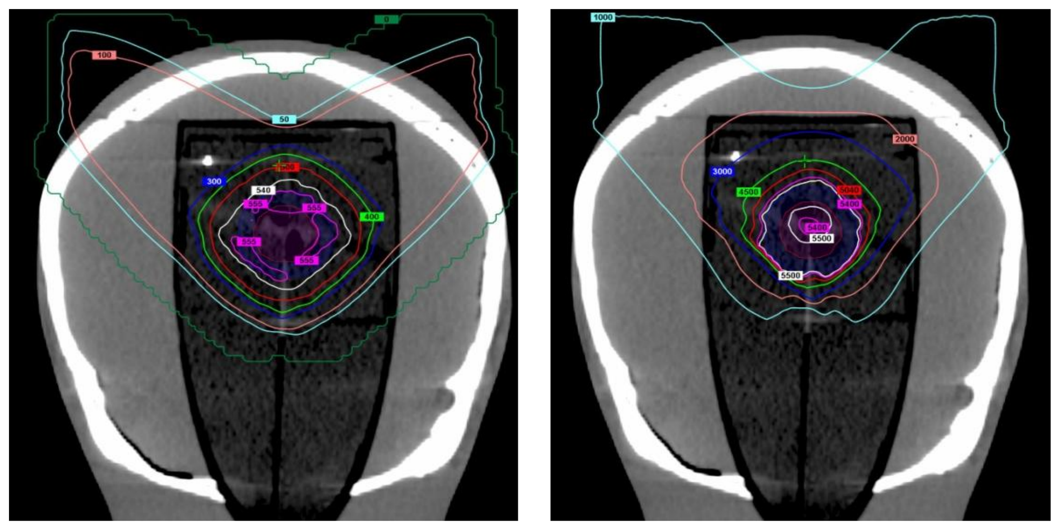
Figure 1. The HU-RSP calibration curve for the Eclipse treatment planning system, with phantom materials plotted

Both MR- and CT-compatible inserts were created, with the aim of replicating real-life simulation of brain tumor patients. The phantom was imaged with MRI using a water-filled cylindrical insert containing a spherical target of 2 cm in diameter. It was then imaged with CT using the solid polyethylene (RSP: 0.997, HU: -34) dosimetry insert, containing Radiochromic film and TLD-100 capsules. The phantom and inserts are shown in **Figure 2.**

Figure 2. Head phantom with dosimetry insert (L) and imaging insert (R)

The MRI and CT image sets were fused in the Eclipse proton treatment planning system and used to delineate the target and create a plan. A passive scatter plan was created for a prescribed dose of 5.4 Gy delivered with three fields: Left Vertex, Right Vertex, and Posterior-Anterior. Isodose distributions can be observed in **Figure 3a**. The modulated spot scanning plan was created for a prescribed dose of 4.9 Gy with just two beams: Left Vertex and Right Vertex. Isodose distributions can be seen in **Figure 3b**.

Results Continued:



a. b.

Figure 3. Eclipse treatment planning posterior snapshots for (**a.**) passive scattering and (**b.**) modulated spot scanning

The treatment plans were delivered with the dosimetry insert loaded with Radiochromic film in the sagittal and coronal planes, and TLD-100 capsules in the right anterior and left posterior quadrants. Each plan was delivered three separate times.

After delivering each treatment plan three separate times, we analyzed the absolute doses, dose distributions, and distance to agreement of the treatments, utilizing the TLD and Radiochromic film from the dosimetry insert. Using gamma analysis, with a pixel passing for $\gamma \leq 1$and failing if $\gamma > 1$, we compared the film profiles with the treatment plan dose profiles. We examined agreement criteria of both ±5%/3mm and ±5%/5mm for the gamma analysis. An example of the gamma analysis for one of the passive scatter trials is illustrated in **Figure 3**, showing 91.5% agreement with criteria of 5%/3mm.

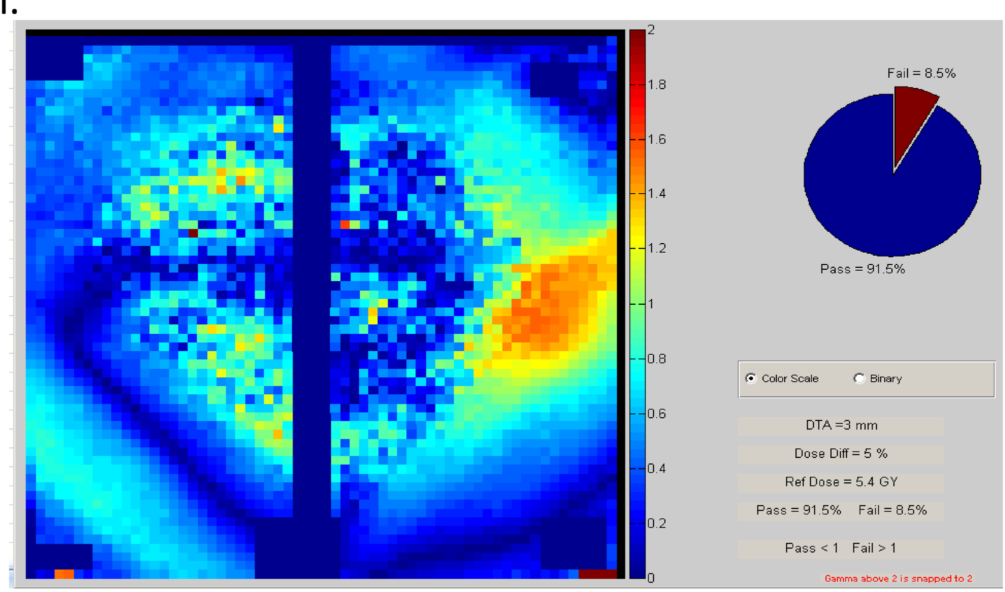


Figure 3. Coronal film gamma analysis for Trial 1 of the passive scattering plan

The passive scattering plans had average gamma pixel pass rates of 91.9% for 5%/3mm agreement, and 97.4% for 5%/5mm agreement. The modulated scanning plans had average gamma pixel pass rates of 90.4% for 5%/3mm agreement, and 98.4% for 5%/5mm agreement. The data for each proton delivery system and both gamma criteria is shown in **Table 1.**

2D Gamma Percentage of Pixels Passing 5%/3mm Criteria

		Passive Scattering		Modulated Spot Scanning	
		5%/3mm	5%/5mm	5%/3mm	5%/5mm
Trial 1	Coronal	91.5%	98.7%	88.1%	99.0%
	Sagittal	93.9%	94.7%	97.3%	99.9%
Trial 2	Coronal	91.3%	97.6%	84.9%	98.6%
	Sagittal	91.9%	98.6%	98.8%	99.7%
Trial 3	Coronal	88.0%	96.3%	80.6%	93.6%
	Sagittal	94.9%	98.6%	92.9%	99.7%

Table 1. Gamma analysis pass rates for 5%/3mm and 5%/5mm criteria for passive scattering, modulated scanning beams

Point dose comparisons for both the passive scattering and modulated spot scanning irradiations are illustrated in **Table 2**, where the doses measured by the TLD powder are compared to treatment planning estimated doses

Results Continued: For the passive scattering treatment plan, there was less than a 3% difference between point doses calculated by the treatment planning system and those measured by TLD. For the modulated spot scanning treatment plan, there was agreement within <1% between the treatment planning system and TLD measurements for point doses. Both the spot scanning and passive scattering systems showed a covariance of less than one percent, meeting our desired reproducibility criteria of 3%.

	Passive Scattering		Modulated Spot Scanning	
TLD Location	Right Anterior	Left Posterior	Right Anterior	Left Posterior
Calculated Dose [cGy]	540	545	490	490
Measured Dose Avg. [cGy]	525.6	532.4	489.9	491.8
COV	0.78%	0.75%	0.15%	0.56%
Measured/Calculated Dose	0.973	0.977	1.000	1.004

Table 2. Point dose comparisons between treatment planning calculated doses and TLD-measured doses for passive scattering and modulated spot scanning plans

Distances to agreement (DTAs) were calculated for each trial of each beam delivery system. These were done by comparing the linear regressions of the profiles of the treatment planning system and the film measurements in the dose falloff region. The DTAs were averaged over each trial in the superior, inferior, anterior, posterior, right, and left directions. Results for the DTA measurements are shown in Table 3. For both the passive scattering and spot scanning plans, shifts were within the 3mm margins on all sides of the target dose profile except the right side, which we suspect was caused by a rotation of the phantom due to a loose leveling screw.

Average Distances to Agreement

	Passive Scattering	Modulated Spot Scanning
Left	0.6 ± 0.6 mm	0.1 ± 0.8 mm
Right	3.7 ± 0.4 mm	3.4 ± 0.5 mm
Superior	0.6 ± 0.7 mm	2.2 ± 1.7 mm
Inferior	-1.1 ± 0.6 mm	-1.8 ± 0.9 mm
Anterior	0.8 ± 0.8 mm	0.0 ± 0.5 mm
Posterior	-0.8 ± 0.5 mm	-1.2 ± 0.4 mm

Table 3. Average DTAs for each direction for both treatment systems

Discussion: While the distance-to-agreement shifts in the R-L direction were larger than desired, these DTAs represent just one slice of a plane of data, and the overall shifts demonstrated by the phantom were acceptable. The phantom showed good pixel pass rates for the more thorough gamma analysis with both the 5%/3mm and 5%/5mm criteria, and had a reproducibility within the RPC's 3% criteria. The head phantom has been deemed acceptable for the integration into the RPC phantom audit program.

References:

[1] Weber, D.C., et al., *Spot-scanning proton radiation therapy for recurrent, residual or untreated intracranial meningiomas.* Radiotherapy and Oncology, 2004. **71**(3): p. 251-258.
[2] Hug, E.B., et al., *Proton radiotherapy in management of pediatric base of skull tumors.* International Journal of Radiation Oncology*Biology*Physics, 2002. **52**(4): p. 1017-1024.

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