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Development and Implementation of an Anthropomorphic Pediatric Spine Phantom for the Assessment of Craniospinal Irradiation Procedures in Proton Therapy

Dana J. Lewis, Paige A. Summers, David S. Followill, Narayan Sahoo, Anita Mahajan, Francesco C. Stingo, & Stephen F. Kry
Department of Radiation Physics, The University of Texas M.D. Anderson Cancer Center, Houston, TX

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Introduction

The purpose of this study is to design an anthropomorphic pediatric spine phantom for use in the evaluation of proton therapy facilities for clinical trial participation by the Imaging and Radiation Oncology Core (IROC) Houston QA Center (formerly the Radiological Physics Center).

Unlike external beam radiotherapy using photons and/or electrons, protons deposit dose over a finite range based on their energy, with a maximum dose deposition at the end of the range. This maximum dose deposition, called the Bragg peak, is useful for treating tumors as it allows for protons to deliver the majority of its dose to the target volume while sparing the surrounding healthy tissue [1,2]

With the number of proton therapy facilities increasing nationwide, it is important to establish accuracy and consistency in the dose delivered in patient treatments. IROC Houston uses anthropomorphic phantoms as a part of the mailable audit program to verify dose delivery for various treatment techniques. The spine phantom includes durable materials that can be used in radiation dosimetry as tissue substitutes when irradiated with protons, along with a simulated spine curvature. The inclusion of multiple tissue substitutes in the phantom increases heterogeneity and the level of difficulty for institutions to conduct a successful treatment.

Materials/Methods

This phantom was designed to perform an end-to-end audit of the proton spine treatment process, including simulation, dose calculation by the treatment planning system (TPS), and proton treatment delivery. The design, shown in **Figure 1**, incorporated materials simulating the thoracic spinal column of a pediatric patient, along with two thermoluminescent dosimeter (TLD)-100 capsules and radiochromic film embedded in the phantom for dose evaluation.

Contact:DLewis2@mdanderson.org

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Methods continued

Fourteen potential materials were tested to determine relative proton stopping power (RSP) and Hounsfield unit (HU) values. Each material was CT scanned at 120kVp, and the RSP was obtained from depth ionization scans using the Zebra (IBA) multi-layer ion chamber (MLIC) at two energies: 160 MeV and 250 MeV [3]. To determine tissue equivalency, the measured RSP for each material was compared to the RSP calculated by the Eclipse TPS for a given HU.

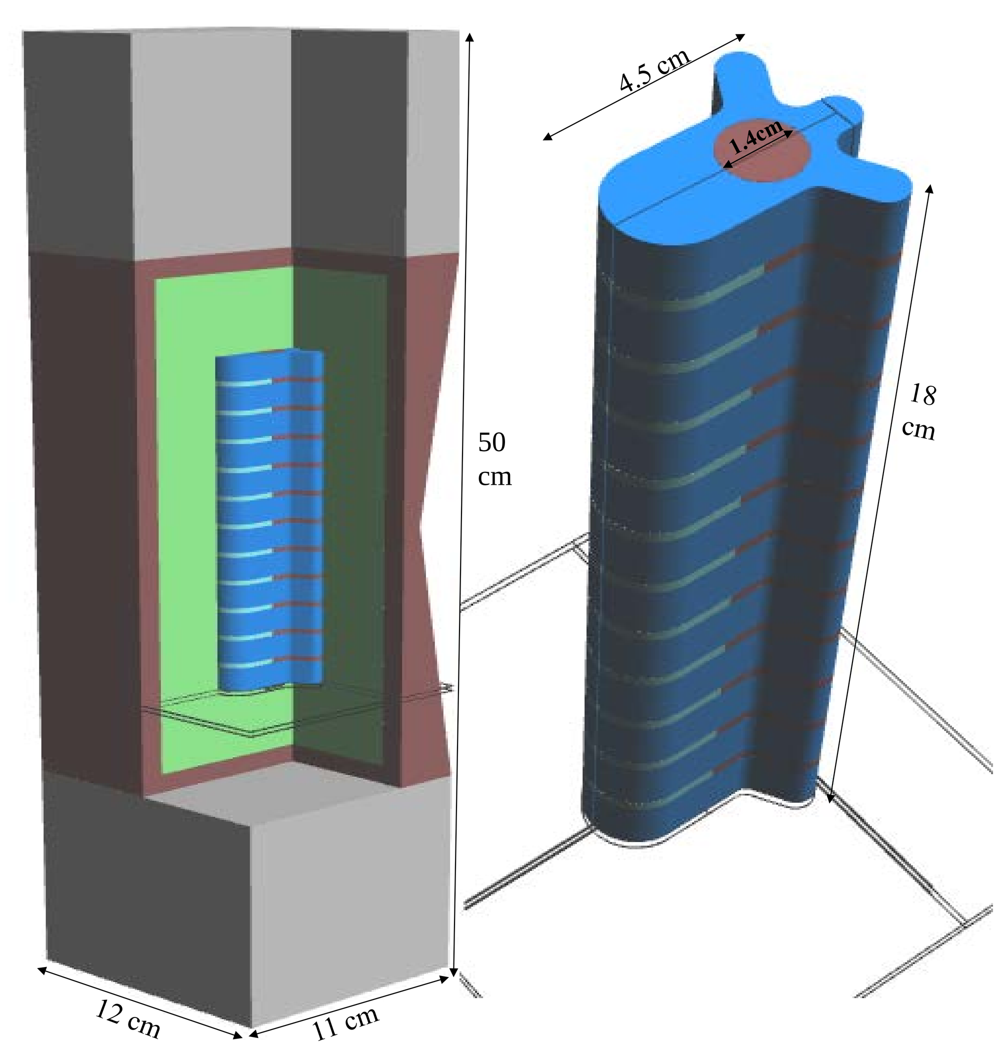

Figure 1. 3D views of the phantom design. The materials selected as bone, tissue, and cartilage substitutes were Techron HPV Bearing Grade (blue), solid water (maroon), and blue water (light blue), respectively. Radiochromic film (green) is placed in the sagittal and coronal planes. The spinal curvature is simulated by a wedged piece of solid water. Polystyrene (gray) is added in the superior-inferior direction, extending the length to 50cm in order to accommodate the beam divergence when using a junction.

Results

The materials selected as bone, tissue, and cartilage substitutes were Techron HPV Bearing Grade (Boedeker Plastics, Inc.), solid water (Gammex, Inc.), and blue water (Standard Imaging), respectively.

The HU-RSP curve for the Eclipse treatment planning system comparing the phantom materials tested is shown in **Figure 2**. Because most craniospinal treatments use a 160 MeV beam, the stopping powers corresponding to this energy were used for determining tissue equivalency.

Table 1 shows data comparing measured RSP measurements for phantom materials tested at 160 MeV to the RSP calculated by the Eclipse TPS for a given HU. The measured RSP agreed with the RSP calculated by Eclipse within 1.2%.

Results continued

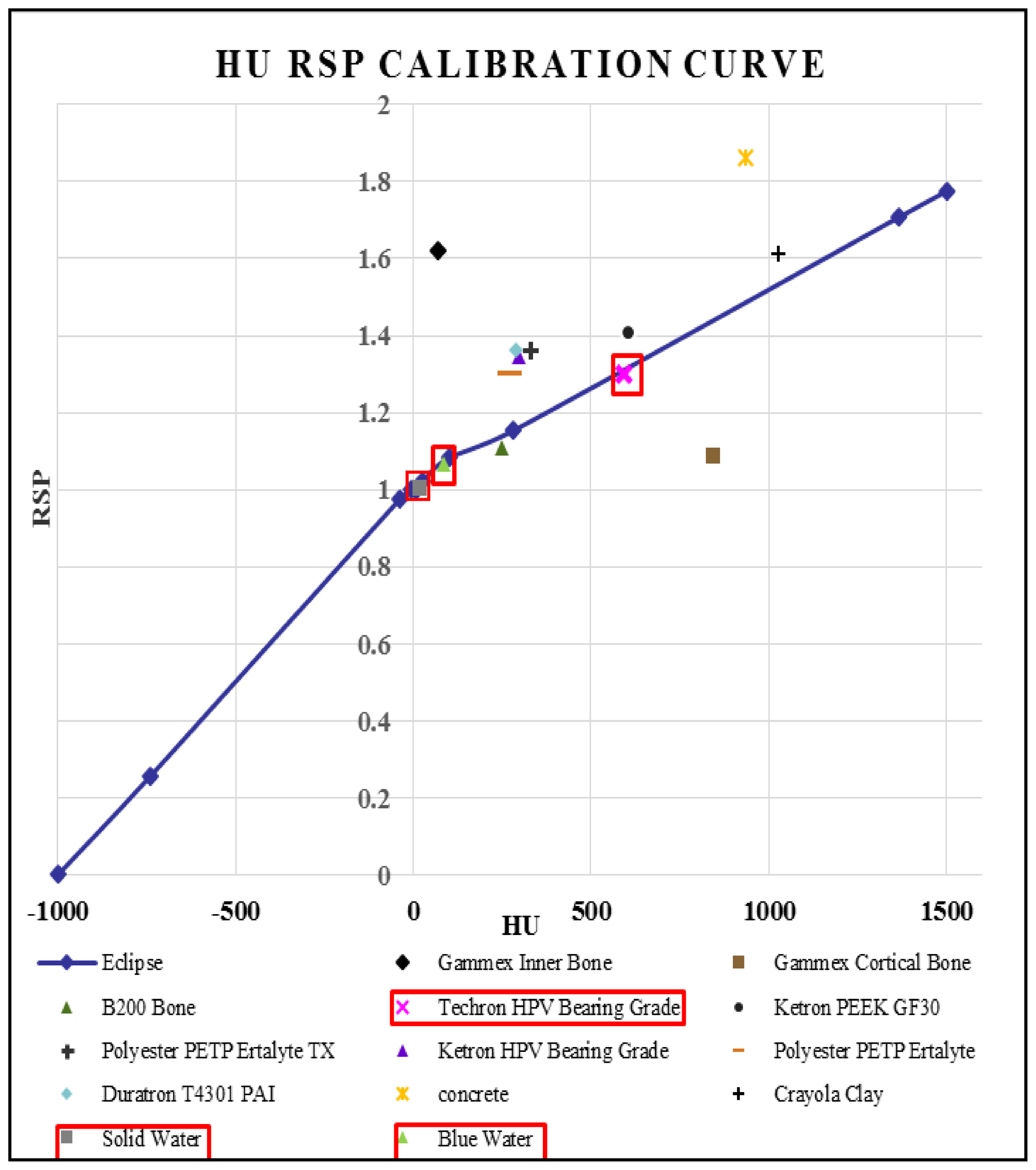

Figure 2. Relative Stopping Power (RSP) versus Hounsfield unit calibration curve comparing tested materials with Eclipse treatment planning system. The selected phantom materials are highlighted.

Table 1

Material Name	Theoretical RSP at 160 MeV	Measured RSP at 160 MeV	Percent Error (%)
Blue Water	1.07	1.07	0.3
Solid Water	1.01	1.00	0.6
Techron HPV Bearing Grade	1.31	1.30	1.2

Table 2 shows the data comparing the relative stopping power measurements at 160 MeV and 250 MeV for each tested phantom material. The largest difference between the RSP at the two proton energies was less than 1.8%.

Table 2

Material Name	RSP at 160 MeV	RSP at 250 MeV	Mean RSP	Percent Difference (%)
Gammex Inner Bone	1.61	1.60	1.61	0.99
Gammex Cortical Bone	1.09	1.08	1.09	1.29
B200 Bone	1.10	1.09	1.10	0.92
* Techron HPV Bearing Grade	1.30	1.28	1.29	1.34
Ketron PEEK GF30	1.41	1.39	1.40	1.38
Polyester PETP Ertalyte TX	1.36	1.34	1.35	1.72
Ketron HPV Bearing Grade	1.35	1.33	1.34	1.58
† Polyester PETP Ertalyte	1.30	1.28	1.29	1.75
Duratron T4301 PAI	1.36	1.34	1.35	1.31
§ Concrete	N/A	1.86	1.86	N/A
Crayola Clay	1.61	1.61	1.61	0

*This data corresponds to the bone tissue substitute selected for the phantom.
†The largest difference between the RSP at two proton energies was calculated for this material.
§ The 160 MeV proton beam did not penetrate the sample.

Preliminary Phantom Evaluation Results

The following attributes were evaluated: absolute dose, junction match and right/left dose profile alignment. Listed are preliminary results from the passive scatter irradiations. Each film plane was evaluated using gamma analysis criteria of 5%/5mm and 5%/3mm with 85% of pixels passing. **Table 3** shows the data from each criteria evaluation. **Figure 3** shows an example of the gamma analysis in the sagittal plane.

Table 3

2D Gamma Analysis Results

5%/5mm Pass Criteria			5%/3mm Pass Criteria		
Trial	Coronal	Sagittal	Trial	Coronal	Sagittal
1	99.58	92.09	1	96.43	75.81
2	99.19	94.64	2	98.89	87.72
3	99.39	92.84	3	95.13	89.14

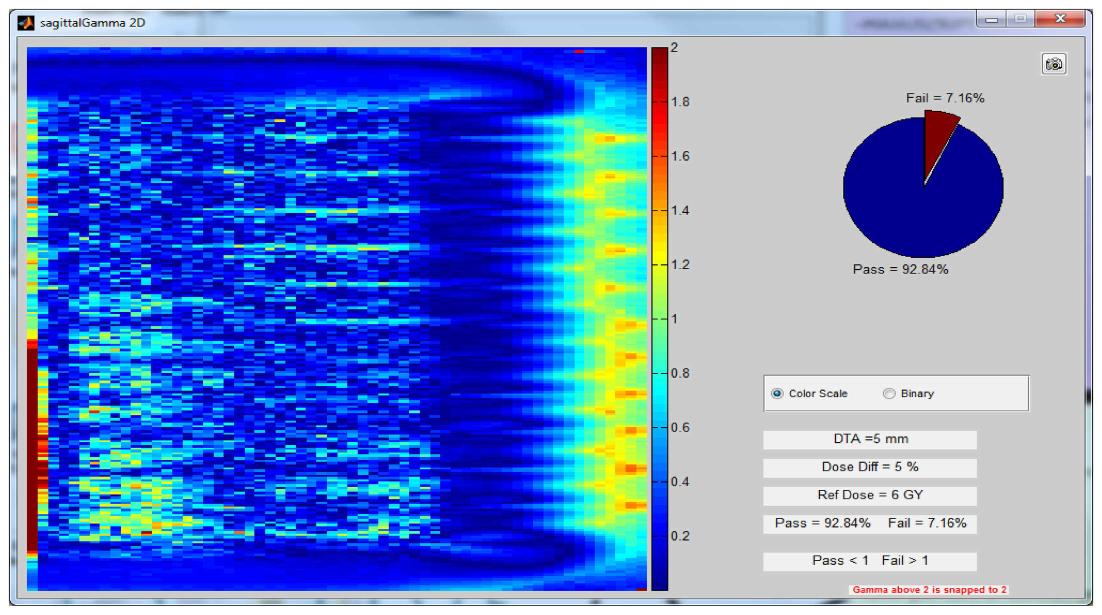

Figure 3. Sagittal film Gamma analysis for Trial 3 with a 5%/5mm passing criteria.

Table 4 shows the DTA data with respective criteria for each profile. All irradiations successfully passed.

Table 4

Average Distance to Agreement (DTA) data

Film Plane	DTA (mm)	Criteria
Coronal R/L -Field 1	2.07	5mm
Coronal R/L -Field 2	1	5mm
Sagittal A/P -Field 1	1.3	5mm
Sagittal A/P -Field 2	1	5mm
Coronal S/I Junction Shift	1.8	5mm
Sagittal S/I Junction Shift	3.01	5mm
% Dose Difference-Coronal	2.01	7%
% Dose Difference-Sagittal	1.16	7%

Table 5 shows the absolute dose agreement results. All TLDs passed the ±5% criteria.

Table 5

TLD Point Dose Agreement

TLD Location	Right Superior	Left Inferior
TPS Calculated RBE Dose	610.2	617.9
Measured RBE Dose	615.9	627.7
Measured/Calculated Ratio	1.009	1.016
COV (%)	0.485	0.352

Conclusions

An anthropomorphic pediatric spine phantom was designed to evaluate proton therapy delivery. Multiple tissue substitutes increase the level of difficulty for institutions to pass evaluation. The phantom will be tested at several institutions before deemed acceptable for use by IROC Houston.

References

1) R.R. Wilson, "Radiological use of fast protons," Radiology 47, 487-491 (1946).
2) ICRU, "1 INTRODUCTION," JOURNAL OF THE ICRU, 11-20 (2007)
3) M.F. Moyers, M. Sardesai, S. Sun, D.W. Miller, "Ion Stopping Powers and CT Numbers," Medical Dosimetry 35, 179-194 (2010).