Proton Therapy Tissue-Equivalence of 3D Printed Materials

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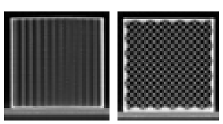
Purpose: This work investigated the proton tissue-equivalence of various 3D printed materials, as well as how various printing factors affect the HU and relative linear stopping power (RLSP) of the materials.

3D printing can be used to create tissue-equivalent proton phantom materials. This project is innovative because unlike previous material studies, we considered several key factors that affect the dosimetric characteristics in proton beams. However, material properties vary widely depending on the orientation that the material was irradiated (with respect to print infill). Not all plastics are suitable proton-equivalent materials.

Methods: Three 3D printers were used to create 5 cm cubic phantoms made of different plastics with varying percentages of infill. White resin (WR), polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and NinjaFlex (NF) plastics were used. The infills ranged from 10% to 100%. Linear (L) and Hexagonal (H) infill patterns were used.

Each phantom was scanned with a CT scanner to obtain the HU value. Separate CT scans were performed with the table movement perpendicular and parallel to the print direction for each material.

The relative linear stopping power (RLSP) was determined using a multi-layer ion chamber (MLIC) in a 200 MeV proton beam. The RLSP was measured both parallel and perpendicular to the print direction for each material. A baseline depth dose curve was obtained with the MLIC. Each printed cube was placed in front of the MLIC to measure the shift in range. From this shift, the RLSP was determined using the formula from Moyers, et. al. (1).



A. B.

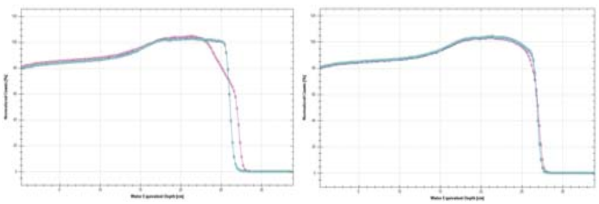
Figure 1. Axial slices of 2 CT scans of ABS 20% linear infill where the direction of CT table movement was perpendicular to the print direction (A) and parallel to the print direction (B).

Results: The HU values of the materials ranged from lung-equivalent (-903 HU) when using a low percent infill, to soft-tissue-equivalent (160 HU) when using a high percent infill. The orientation of the print direction during the CT scan affected the CT image and HU obtained. ABS 20% linear infill had the largest difference. A mean difference of 100 HU between CT scan orientations was measured (Figure 1). The linear infill patterns had larger HU differences between CT scan orientations (up to 100 HU) than the hexagonal infill patterns (up to 7 HU). The linear infill patterns also had a larger standard deviation (up to 26 HU) between HU measurements on different slices in a single CT scan orientation than the hexagonal infill patterns (up to 6 HU).

Results: Larger print resolution (0.3 mm compared to 0.2 mm) showed a larger HU difference between CT scan orientations and a larger standard deviation between slices for a single CT scan orientation. Generally, there was a large variation in HU value slice by slice when the print direction was perpendicular to the motion of the CT table (up to 26 HU standard deviation over several slices). Because of this variability in the perpendicular orientation, the mean HU values from the CT scans with the print direction parallel to the table movement were used for RLSP analysis.

The RLSPs were determined using both the distal 90% point and the distal 80% point. There was a smaller standard deviation between measurements using the 80% point. The 80% point was used for final analysis.

Two different colors of PLA were tested using the same fill pattern and percent infill. There was a small difference in HU observed (9 HU), the RLSP measurements were within 5%.



ABS20L **PLA10L**

Figure 2. Depth dose measurements for ABS 20% linear infill and PLA 10% linear infill.

Results: Proton beam distal degradation was observed in many of the depth dose measurements. This phenomenon was observed more in cubes with lower percent infill (<50%), particularly when the proton beam was parallel to the scan direction. Figure 2 shows an example of the degradation in the parallel orientation. For the ABS 20% infill, the blue curve is the SOBP with the 5 cm cube in the beam path with the proton beam perpendicular to the print direction. The purple curve is the SOBP with the 5 cm cube in the beam path with the proton beam parallel to the print direction. The RLSPs of the two orientations differ by 11%, using the distal 80% point to calculate RLSP. Due to distal degradation of the beam in the parallel irradiation orientation, the distal penumbra (80%-20%) increases from 0.6 cm in the perpendicular beam to 2.3 cm with the parallel orientation.

Figure 2 also shows the depth dose curves for PLA 10% linear infill, which was distinct from other materials tested because the depth dose showed degradation in both the parallel and perpendicular irradiation orientations. Despite the similar shape in curves, there is still a 7% difference between RLSP in the parallel and perpendicular directions.

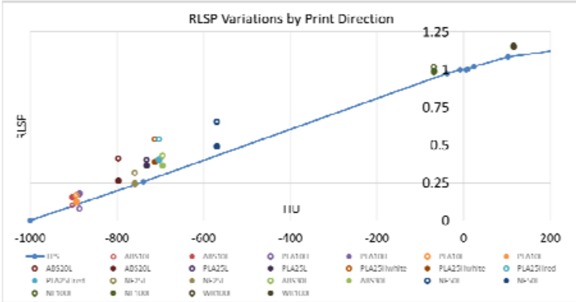


Figure 3. HU vs. RLSP. The blue curve is the reference TPS curve. The open circles represent measurements with the beam direction parallel to the print direction and the closed circles represent the RLSP for the beam direction perpendicular to the print direction. Materials are identified by their plastic, percent infill, infill pattern, and color (if applicable).

Results: Our tolerance for agreement between the RLSP of a phantom material and the clinical conversion curve is ±5%. Only two materials fell within that criterion: ABS (10% infill, with the proton beam parallel to print direction), and NinjaFlex (25% and 100% infill, with the proton beam perpendicular to the print direction). However, when the orientation of the material was changed relative to the proton beam, the RLSP did not fall within 5%. Results for the parallel and perpendicular orientations of the proton beam relative to the print direction are shown in Figure 3. The RLSP of the two orientations differed by more than 5% for all the materials that didn't have 100% infill.

Conclusions: It is important to take into consideration the variability in both HU value and RLSP depending on the orientation of the print direction relative to the CT x-ray tube and the proton beam. For phantom design purposes, the CT orientation could be properly taken into account as most institutions scan phantoms in the same orientation. But for proton beam arrangement, the variability in RLSP could be more of a problem since a variety of gantry and couch angles can be used for treatment. For IROC phantom purposes, the NinjaFlex 100% infill met our criteria of falling within 5% of the clinical HU-RLSP curve, but only for one orientation. Other print patterns could be tested for smaller RLSP variability with print direction. White resin 100% infill was very close to our criterion, differing from the clinical curve by 6% in either orientation.

Reference: 1. Moyers MF, Sardesai M, Sun S, Miller DW. Ion stopping powers and CT numbers. Med Dosim. 2010;35(3):179–94.

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