Characterization of CT Hounsfield Units uniformity of 3D printed materials for proton therapy

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INTRODUCTION

Previous studies have evaluated CT Hounsfield Units (HU) uniformity for a variety of 3D printing techniques and for proton and non-proton applications; however, 3D printing technology and materials are evolving at an incredibly rapid pace and differences in methodology and results reporting between previous studies prevent straightforward comparison of 3D printer-material combinations.

PURPOSE

The primary purpose of this work was to evaluate the HU uniformity of 3D printed samples produced by twelve 3D printer-material combinations.

A secondary, inherent purpose was to develop a procedure for HU uniformity evaluation which addresses comprehensive sampling of the object volume, addresses excluding partial volume affected voxels and investigates repeatability as a function of several potential dependencies previously identified in the literature (Michiels et al., 2016; Zou et al., 2015).

METHOD

- A sample geometry of 5 cm x 5 cm x 2 cm was identified as relevant for both HU uniformity and (forthcoming) Bragg peak shift/relative proton stopping power (RSP) measurements.
- Solid 3D printed samples (100% in-fill) were produced with the twelve 3D printer-material combinations given in Table 1. For a subset of these combinations, multiple samples were produced to assess repeatability, material batch, print orientation, print time, and print geometry dependence (see results Table 1).
- CT scans of all samples were acquired using 120 kVp and imported into a clinical treatment planning system (Eclipse, Varian Medical Systems, Palo Alto, CA). Samples were visually reviewed to identify and exclude failed prints with large scale, patterned defects. A threshold-based contouring tool was applied to identify samples within the CT images,
- In-house MATLAB (The MathWorks, Inc.) code was then used to identify and exclude peripheral partial volume affected regions and evaluate descriptive statistics (mean HU μ, standard deviation σ) on the remaining sample volume, both overall and in 9 sub-regions (dividing through the 5 cm x 5 cm dimension into 3 x 3 sub-regions), for each sample.
- Results were compared to a ≤10 HU criterion to predict if the heterogeneity-associated proton range uncertainty of each 3D printed material would be acceptable for use during clinical proton treatment planning.
- A clinical HU - RSP calibration curve was then used to project calculated RSP values from the (μ +/- σ) HU.

RESULTS

- FDM-PLA and SLA-Clear Resin were the most thoroughly investigated printer-material combinations (Table 1). They demonstrated good reproducibility with no dependence on material batch, print orientation, and print geometry. The failed print rate and HU uniformity were however, found dependent on printer maintenance for FDM technology but this was not observed for SLA or Polyjet.
- HU uniformity, characterized by the standard deviation in HU on the overall sample volume ($\sigma_{HU\ overall}$), ranged from +/- 3 HU to +/- 57 HU.
- Within-print repeatability showed consistent print uniformity across sample volume for all prints whose overall HU uniformity met our $\sigma_{HU\ overall} \leq 10$ HU criterion, while this was not the case for prints failing the uniformity criterion (Figure 1a,b vs. c).
- The mean HU of printed materials that met the uniformity criterion ranged from -65 HU to 237 HU, with the standard deviation ranging from 3 to 9 HU. This translated into RSP from 0.978 +/- 0.004 to 1.144 +/- 0.002 (Table 1).
- Between-print repeatability, for the available printer-material combinations, demonstrated HU uniformity is reproducible, conditional on visual assessment of CT images to exclude failed prints (Figure 1d).

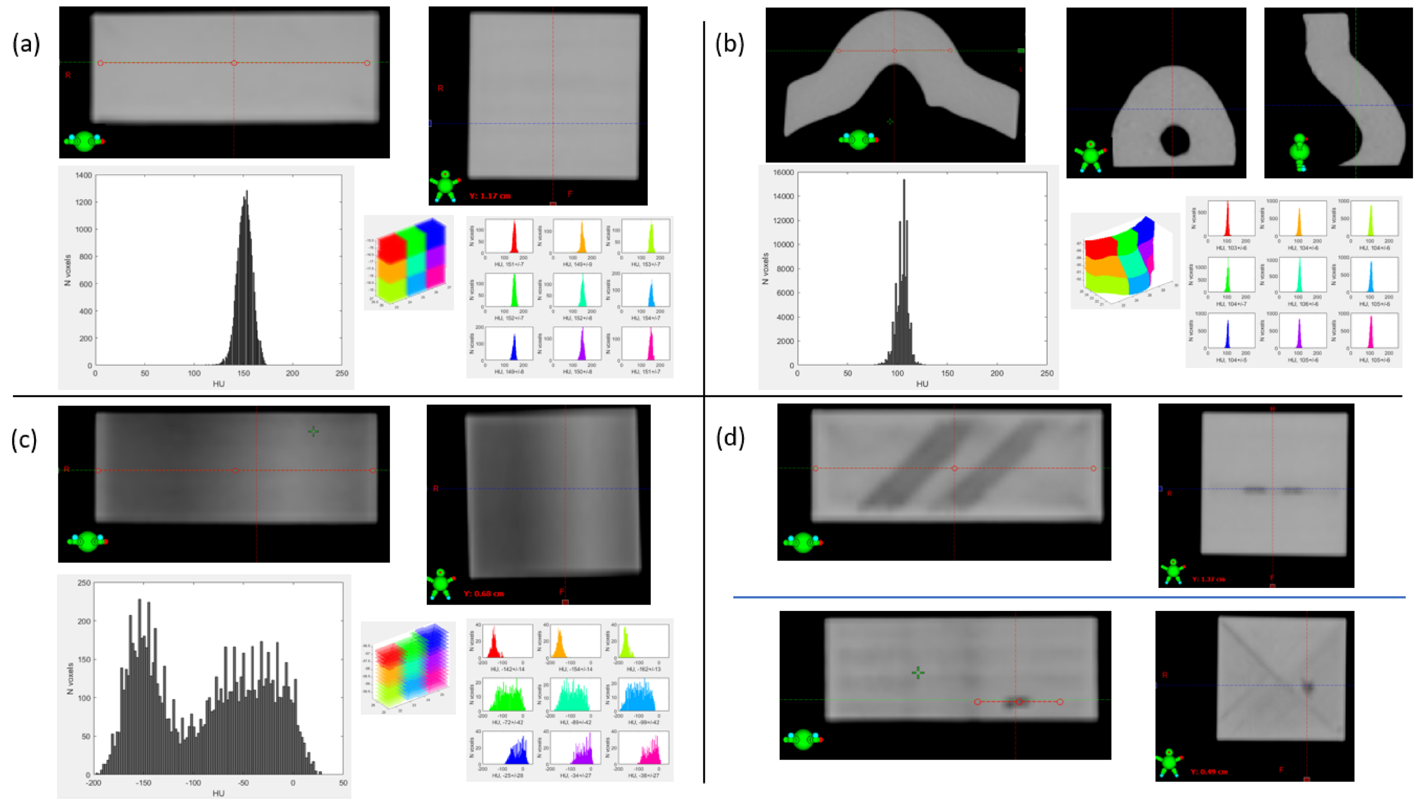

Figure 1. Example CT images (Eclipse, Varian Medical Systems, Palo Alto, CA) +/- analysis of samples with: $\sigma_{HU\ overall} \leq 10$ HU: standard (a) and clinical (nose) geometry (b), vs. sample with $\sigma_{HU\ overall} > 10$ HU = fails uniformity criterion (c) and 2 sample failed (FDM) prints (d). The CT image display for (c) is W/L = 350/0 HU, for all others a soft tissue W/L is used (W/L = 350/50 HU).

Print technique	3D Printer	Material	N prints	50cc print time (h:mm)	TDS material density (g/cc)	HU (μ±σ)	RSP (μ±σ)	HU within-print repeatability [min max]	HU between-print repeatability [min max]	HU material batch [min max]	HU clinical print geometry [min max]	HU horizontal print orientation [min max]
FDM	AirWolf Axiom 20	3D-Fuel Standard PLA	5	2:11	1.25	161 ± 5	1.111 ± 0.002	μ [159 163] σ [4 5]	-	-	μ [161 169] σ [5 6]	μ [159 161] σ [4 5]
	Raise3D Pro2+	3D-Fuel Pro PLA (APLA+)	2	2:32	1.22	148 ± 8	1.106 ± 0.003	μ [136 153] σ [5 8]	μ [145 151] σ [6 9]	-	-	-
SLA	FormLabs Form2	Formlabs Clear Resin	10	4:07	1.15	107 ± 4	1.088 ± 0.002	μ [101 115] σ [2 9]	μ [± 1] σ [± 1]	μ [± 1] σ [± 1]	μ [106 107] σ [4 5]	μ [106 107] σ [4 5]
SLA (DLP)	3DSystems Figure 4	NextDent Crown&Bridge	1	2:30	1.3	237 ± 4	1.144 ± 0.002	μ [231 242] σ [2 7]	-	-	-	-
Polyjet	Stratasys Objet 500	Vero PureWhite	2	-	1.17 – 1.18	138 ± 5	1.101 ± 0.002	μ [136 140] σ [4 5]	μ [± 1] σ [± 1]	-	-	-
		Agilus30	1	-	1.14 – 1.15	87 ± 4	1.084 ± 0.001	μ [86 89] σ [3 4]	-	-	-	-
	Stratasys J750	Vero PureWhite	2	-	1.17 – 1.18	138 ± 4	1.101 ± 0.002	μ [137 139] σ [3 4]	μ [± 1] σ [± 1]	-	-	-
		Agilus30	2	-	1.14 – 1.15	87 ± 3	1.084 ± 0.001	μ [86 89] σ [2 4]	μ [± 1] σ [± 1]	-	-	-
MJF	HP Jet Fusion 5200	HP 3D High Reusability PA 12	1	-	1.01	-65 ± 3	0.978 ± 0.003	μ [-67 -63] σ [2 4]	-	-	-	-
		BASFUltrasint™ TPU011	1	-	1.1	-87 ± 58	0.955 ± 0.061	μ [-162 -25] σ [13 42]	-	-	-	-
	HP Jet Fusion 580	HP 3D High Reusability CB PA 12	1	-	1.03	0 ± 16	1.027 ± 0.005	μ [-22 17] σ [3 14]	-	-	-	-
SLS	3DSystems sPro230	DuraForm GF	1	-	1.3	486 ± 12	1.264 ± 0.005	μ [480 491] σ [10 14]	-	-	-	-

Table 1. Summary of HU uniformity and projected proton relative stopping power (RSP). Within-print repeatability was evaluated based on the nine sub-regions/sample, between-print repeatability was evaluated based on 2 - 3 print job iterations with the same material batch. For reference, technical data sheet (TDS) material densities and print times are also provided. FDM = fused deposition modelling, SLA = stereolithography, DLP = digital light processing, MJF = Multi Jet Fusion, SLS = selective laser sintering, PLA = polylactic acid, TPU = thermoplastic polyurethane, PA = polyamide.

DISCUSSION

- Through access to a variety of in-house print technologies/materials and samples sourced from external 3D printing suppliers, this study provides a direct and detailed comparison of CT HU uniformity across a broad spectrum of current 3D printing technologies and materials.
- Previous literature (Michiels et al., 2016; Zou et al., 2015) identified several potential dependencies for 3D printed material radiological uniformity. For the printer-material combinations evaluated within this work, these dependencies were not observed in the CT-based HU uniformity; however print failure - quantified by visual assessment of large scale, patterned defects in the CT images of the 3D printed samples - was found to be linked to printer maintenance for FDM technology.
- Additionally, previous studies did not provide within-print or between-print radiological repeatability measurements. This work demonstrated that a $\sigma_{HU\ overall} \leq 10$ HU criterion could be used to differentiate samples with vs. without within-print repeatability and that the $\sigma_{HU\ overall} \leq 10$ HU criterion was maintained for between-print repeatability for all 3D printer-material combinations where this was evaluated.

CONCLUSIONS

- Most 3D printer-material combinations investigated in this work met our CT-based radiological uniformity criterion and can therefore be considered for use in proton therapy applications.
- The two MJF and the SLS printer-material combinations were the exception, where their overall HU uniformity and HU within-print repeatability both exceeded the σ ≤10 HU threshold criterion.
- Print failure rate was found dependent on printer maintenance for FDM technology
- Water tank-based, depth dose range shift measurements, to determine the actual RSP, are the next step in this work.

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REFERENCES

1. Michiels S et al. Towards 3D printed multifunctional immobilization for proton therapy: Initial materials characterization. *Medical Physics 2016*;43(10); 5392–5402.
2. Zou W. et al. Potential of 3D printing technologies for fabrication of electron bolus and proton compensators. *Journal of Applied Clinical Medical Physics 2015*; 16(3); 90–98.

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