WATER EQUIVALENCE OF VARIOUS 3D PRINTED MATERIALS FOR PROTON THERAPY — MONTE CARLO SIMULATION, TREATMENT PLANNING MODELLING AND VALIDATION BY MEASUREMENTS*

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In this article, Water Equivalent Ratio (WER) of three selected materials: Polylactic Acid (PLA), Acrylonitrilebutadiene Styrene (ABS) and Polyethylene Terephthalate Glycol (PETG) — commonly used in additive manufacturing technology — was measured on 60 MeV proton beam and compared with values predicted by Treatment Planning System (TPS) and Monte Carlo (MC) simulation. The agreement within 1–3% and 1–6% was found between results obtained from the measurement with comparison to the MC simulation and TPS, respectively. It was concluded that 3D printable materials can be safely used in proton therapy.

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1. Introduction

3D printing is a versatile emerging technology constantly gaining in popularity, starting from the late 90s to today. Its unique potential can be exploited in different areas of both industry and medicine, such as drug production, radiotherapy or surgical planning [1].

In modern radiotherapy — photon, electron and proton, as well as brachytherapy — 3D printing technology has been used in the production of individualized phantoms, boluses or compensators, brachytherapy applicators as well as equipment supporting the immobilization of the patient [2–5]. For these applications, materials such as thermoplastics or light-cured resins are most commonly used. For treatment planning in proton radiotherapy, knowledge of accurately beam penetration range — and thus the stopping power — in different human tissue or materials used during therapy is essential to provide high precision and maximize the saving of healthy surrounding

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tissues. They are characterized by Water Equivalent Thickness (WET) and corresponding Water Equivalent Ratio (WER). WET is a thickness of liquid water needed to stop the proton beam in the same manner that a certain thickness of the given material. WER is defined as the dimensionless ratio between mass thickness of water (in g/cm^2) corresponding to WET and given material mass thickness (in g/cm^2) [6, 7].

In this study for three different printable materials, WER values were calculated in MC simulation, determined in TPS and measured on 60 MeV proton beam produced in AIC-144 cyclotron at the IFJ PAN in Kraków [8].

2. Materials and methods

Three printable materials were selected for this study: Polylactic Acid (PLA) — $(C_3H_4O_2)_n$, Acrylonitrile Butadiene Styrene (ABS) — $(C_6H_{11}N_0)_n$ and Polyethylene Terephthalate Glycol (PET-G) — $(C_8H_8xC_4H_6xC_3H_3N)_n$.

Three plates with dimensions of 5 × 5 cm and different thicknesses — 0.5, 1 and 2 cm — were printed for each material. A 3D printer (Polish company ATMAT, model Signal XL) working in Fused Filament Fabrication technology (FFF) was used to print the plates. For printing,nozzles with a diameter of 0.8 mm were used and layer height 0.25 mm was established. All plates were printed with a 100% filling.

The water phantom was placed at a distance of 85 mm from the snout, on which the printed plates were placed. PTW Marcus chamber type TM23343 was used to measure the depth dose distribution in the isocentre in the water phantom. For MC simulations, the FLUKA code [9] (version 2011.2x.6) was applied. The measurement setup was set in the same way as during the measurements. Theoretical percentage mass content of elements and real values of density and thicknesses of the plates were used. WER was also measured in the TPS Eclipse version 13.6 [10]. The calculation follows the application of a calibration curve that determines the dependence of Hounsfield Units (HU) on the Stopping Power Ratio (SPR). To determine the WER parameter for the printed plates, CT scans were performed on Siemiens Somatom Definition AS tomograph with resolution 0.6 mm and exported to the TPS system. Simple treatment plans were prepared, based on which the WER values of all plates were determined.

3. Results and discussion

WER for all analyzed plates and relative differences between measured and calculated (from both MC and TPS) values are presented in Table I. Relative standard deviation of measured values of WER, normalized to the measured density, are between 0.3% and 0.7% and are comparable with uncertainties of measurements (which also includes Markus chamber and the

TABLE I

Measured and calculated WER for PLA, PET and ABS 3D printing materials. Estimated uncertainties (1 SD) were 0.5–0.7% for measurements, and 2.5% and 0.5% for TPS and MC calculations, respectively.

Sample	Theoretical density ρ [g/cm^3]	Measured density ρ_r [g/cm^3]	WER (WER normalized to ρ_r)			Relative difference [%]	
			meas	TPS	MC	TPS/meas	MC/meas
PLA_0.5	1.24	1.168(12)	1.133 (0.970)	1.132 (0.969)	1.103 (0.945)	0.11	2.61
PLA_1.0		1.2121(43)	1.166 (0.962)	1.131 (0.933)	1.143 (0.943)	3.02	1.98
PLA_2.0		1.2279(38)	1.176 (0.958)	1.126 (0.917)	1.159 (0.944)	4.26	1.44
PET-G_0.5	1.27	1.2080(46)	1.156 (0.957)	1.108 (0.917)	1.190 (0.986)	4.21	−2.94
PET-G_1.0		1.2207(26)	1.175 (0.962)	1.113 (0.911)	1.205 (0.988)	5.28	−2.63
PET-G_2.0		1.2308(23)	1.181 (0.959)	1.104 (0.897)	1.216 (0.988)	6.46	−2.98
ABS_0.5	1.05	1.0035(68)	1.001 (0.997)	1.012 (1.009)	1.012 (1.009)	−1.12	−1.15
ABS_1.0		1.0130(47)	1.020 (1.007)	1.013 (1.000)	1.020 (1.007)	0.69	0.02
ABS_2.0		1.0174(26)	1.020 (1.002)	1.011 (0.994)	1.022 (1.005)	0.82	−0.21

handle positioning uncertainty). They depend mainly on the uncertainty of determination of the distal edge of the Bragg peak, which becomes broader for thicker plates. It is also interesting to note that with increasing plate thickness increased an average plate density. It appears that this is a characteristic feature of this printer — larger elements are filled more accurately, which is visible on CT scans as higher HU inside plates.

The calibration curve for therapy planning is prepared upon a CT scan of the phantom, containing different human tissues equivalent elements inside, what eliminates boundary of large density difference media artifacts and changes the radiation spectrum. Printed plates were surrounded by air during scanning which may cause differences in the TPS calculation relative to the measurement. In addition, the measurement in TPS was made manually, using simple measuring tools. The edges of the plates on CT scans are not clearly visible, so the measurement uncertainty should be increased by the inaccuracy and subjectivity of the decision of the person performing the measurement.

Compliance at the level of 3% of the measurement with MC is satisfactory, when taken into account that theoretical elemental compositions of materials were used for the simulations. It also suggests that the calculations were made correctly with the negligible presence of chemical elements not included in this analysis.

4. Conclusions

It can be concluded that for prints made of ABS material, a high compliance with calculations is obtained. This material can be used during therapy and treated as an element of the patient's body — the use of ABS elements does not require any corrections, the material's stopping power after recalculation using a calibration curve is consistent with measured value. However, when higher densities are needed, materials such as PLA and PET-G require correction and overwriting the correct HU values before including them in the patient's treatment plan. The current calibration curve is dedicated to human tissues and objects similar in volume to the human body, so applying the curve for these plastic materials does not result in correct conversion of obtained HU into stopping power values.

It appears that the only reliable verification is the measurement of the printed material sample and this measurement should be made for each printout that can be used during therapy.

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REFERENCES

[1] R.J. Mobbs *et al.*, *J. Neurosurg. Spine* **26**, 513 (2017).
[2] M. Alssabbagh *et al.*, *Radiat. Phys. Chem.* **135**, 106 (2017).
[3] S. Michiels *et al.*, *Radiother. Oncol.* **128**, 161 (2018).
[4] E.-L. Jones *et al.*, *Brachytherapy* **16**, 409 (2017).
[5] S. Michiels *et al.*, *Med. Phys.* **43**, 5392 (2016).
[6] M.R. Akbari *et al.*, *Appl. Radiat. Isot.* **90**, 89 (2014).
[7] P. de la Vera *et al.*, *Appl. Radiat. Isot.* **83**, 122 (2013).
[8] B. Michalec *et al.*, *Appl. Radiat. Isot.* **68**, 738 (2010).
[9] A. Ferrari *et al.*, FLUKA: A Multi-Particle Transport Code, 2005.
[10] TPS Eclipse version 13.6, Proton Treatment Planning System, manual.