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Abstract

Design and material characterization of cost-effective 3D-printed tissue-equivalent phantoms for radiotherapy quality assurance

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Additive manufacturing (AM) enables the fabrication of patient-specific anatomical models that can support quality assurance (QA) in radiotherapy. However, identifying low-cost printable materials that reproduce the radiological properties of human tissue remains challenging. In this work we systematically evaluated radiological properties of various commonly (ABS, PLA, TPU, etc) and less commonly (combinations of resin PolyJet photopolymers) available 3D printing materials, varying also in-fill densities. These have been studied partly previously, but we included a combined characterization at diagnostic (keV) and therapeutic (MeV) photon energies, rarely included in most works concerning phantom development for radiotherapy, but useful given the somewhat different X-ray interaction mechanisms in both energy regimes. Moreover, we explored a low, medium and high-cost 3D printer. More than 50 cubic samples were fabricated using fused filament fabrication from ten commercially available polymer filaments and with varying infill densities. CT images were acquired and the average Hounsfield Units (HU) for each sample was determined. Mass density (ρ), electron density (ED), and relative electron density (RED) were derived and compared with reference values from ICRU tissue data. To validate performance under therapeutic conditions, the samples were irradiated with megavoltage photon beams and the deposited dose was measured using a micro-diamond detector and compared with treatment planning system (TPS) predictions. The investigated materials with 100% in-fill density exhibited HU values between -94 and 230, ρ values ranging from 0.98 to 1.23 g/cm^3, ED from 3.13 to 3.80×10^{23} electrons/cm^3 and RED ranging from 0.94 to 1.23. Several combinations of filament material and infill density showed radiological properties close to ICRU soft tissue. Measured dose values agreed with TPS calculations within 0.9-1.2%, confirming their suitability for radiotherapy dosimetry. Based on these results, a breast phantom was successfully fabricated using low-cost desktop 3D printing. This work demonstrated a practical workflow for the development of tissue-equivalent phantoms using AM approach. By combining CT-based material characterization with dosimetric validation, several cost-effective polymer materials were identified for the fabrication of realistic radiotherapy QA phantoms. The approach facilitates broader adoption of patient-specific QA tools using accessible 3D printing technologies.

AUTHOR'S STATEMENT
Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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