Characterization of 3D printed material as possible tissue surrogates for ion therapy

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Einleitung

End-to-end (E2E) tests in radiotherapy mimic all workflow steps, in most cases employing an anthropomorphic phantom suitable for both imaging and dosimetry. In particle therapy the use of tissue equivalent phantom materials is a prerequisite for accurately benchmarking the dose prediction by the treatment planning system (TPS) with dosimetric measurements. To determine the beam attenuation, CT numbers (CTN) of the planning CT are translated into physical density (δ) via a heuristic calibration curve. In a further step, the chemical composition based on human tissue [1] and its corresponding stopping power ratio (SPR) is assigned according to the previously derived density [2]. In particle therapy commercial tissue equivalent phantoms are of limited availability. With the increasing number and quality of additive manufacturing (AM) solutions, AM could prove to be a cheap and flexible alternative for producing phantoms for medical purposes. This work aims to characterize additively manufactured materials for the design of an E2E test phantom fulfilling the requirements for ion beam therapy. Both printing quality and tissue equivalency was evaluated.

Material und Methode

For eight samples the water equivalent thickness (WET) was measured via a water column system (Peakfinder, PTW) in a 148.2 MeV proton beam. This was repeated at three different points on a 5x5 cm sample with a thickness t = 1 cm to assess print quality and homogeneity. In addition to the plates for dosimetric purposes, cylindrical plugs were produced for determining CT numbers in a CIRS CT calibration phantom. The employed techniques were fused deposition modeling (FDM) (FunmatPro410, Intamsys), stereolithography (STL) (Form3, Formlabs) and selective laser sintering (SLS) (EOS P396, EOS). Four materials were preselected as possible soft tissue surrogates: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), high impact polystyrene (HIPS) and Elastic 50A. Durable 10K was considered as a bone surrogate. The materials Though2000, WhiteResin and Nylon-12 were selected to mimic other tissues of interest. Reference WER (= WET/t) and SPR (= WER/δ) values are 1.092 (SPR = 1.035) for resin-based soft tissue. For trabecular bone and cortical bone the reference WER values are 1.381 - 3.211 (SPR = 1.154 - 1.681), respectively [2].

The photon attenuation of the cylindrical material samples were evaluated using a protocol similar to [3]. An example of such a CT scan is shown in figure 1. The imaging protocol of choice was a clinical head scan, kVp = 120 V and slice thickness = 2 mm. The CTN distribution was extracted from a volume inside the cylinders, delineated with a 1-2 mm margin to avoid any partial volume effects. The reported physical density values are derived from the protocol specific CTN to density conversion table.

Resultate

The WER of soft tissue candidates ranged from 0.909 to 1.088 (SPR = 0.980 to 1.024), while WERDurable10K was 1.516 (SPR = 0.894). Tough 2000 and WhiteResin showed a WER of 1.168 (SPR = 0.985) and 1.165 (SPR = 0.993), while WERNylon-12 was 0.998 (SPR = 1.040). The measurement uncertainty was below 1.1 % for all samples and laid within setup uncertainties, confirming their homogeneity within detectable limits.

The density prediction of the TPS for the soft tissue surrogates ranged from 0.853 g/cm³ to 1.088 g/cm³, the predicted density for the bone surrogate was 1.447 g/cm³. For Tough 2000 and WhiteResin the predicted density is 1.105 g/cm³ and 1.114 g/cm³, while the prediction for Nylon-12 was 0.987 g/cm³. The standard deviation for the prediction of the FDM printed materials ranged from 2.0% to 4.7%, whereas the standard deviation for the SLS and STL materials was between 0.39% and 0.66%. Investigations of the CTN distributions suggest a deviation from normal distribution for FDM prints; figure 1 shows an example for HIPS. For STL and SLS the CTN adhere to a normal distribution.

Diskussion

The investigated 3D printed materials will enable efficient manufacturing of phantoms for ion therapy. While range measurements did not find major inhomogeneities for any printing method, the distribution of CT numbers suggests otherwise. Further investigations of this discrepancy will help determine the suitability of the selected manufacturing methods. The most promising candidates seem to be Elastic 50A and ABS as soft tissue surrogates, Nylon-12 as breast/fatty tissue surrogate and Durable 10K for medium density bone. Translating the materials' density prediction into range prediction of a treatment planning system will show their usability in an E2E test.

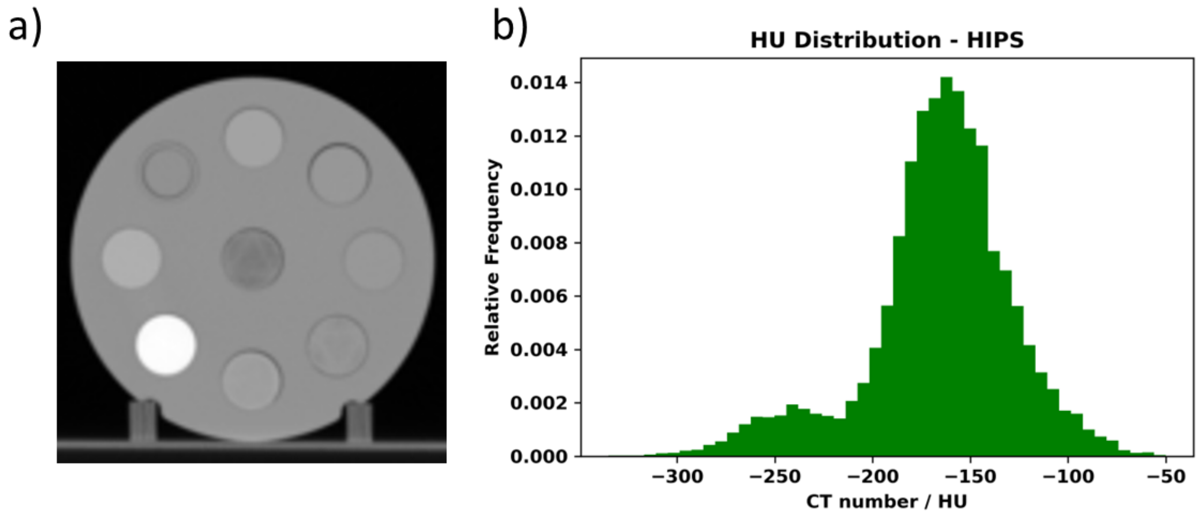

Figure 1: CT scans of 3D printed plugs inserted in the CIRS phantom. a) shows a transversal view of the different inserts with HIPS in the middle. b) shows the distribution of CT numbers inside the HIPS plug.