A Monte Carlo framework to evaluate the radiological properties of 3D-printable materials for proton therapy phantom development

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Introduction

Phantoms consist of human substitute materials and are used to characterise the effect of radiation in tissue for quality assurance (QA) purposes in radiotherapy. 3D-printing is becoming an increasingly popular method for phantom construction due to its low cost and design flexibility. 3D-printers build samples by depositing materials such as plastics using a layer-by-layer method. The choice of materials and printing parameters allows the fabrication of plastics which can be made representative of different tissue types. Different infill patterns may be used to fill the inside of each layer and the infill percentage can be tuned to produce an object with the desired mass density. However, the internal structure of the samples may affect the radiation interactions, particularly with protons, which are sensitive to material compositions. The aim of this work was to develop a Monte Carlo (MC) framework to investigate the impact of printing settings on proton dose deposition and inform the development of novel 3D-printable tissue-substitute materials.

Materials & Methods

A realistic setup of range measurements in proton beams was validated in GATE v8.2. We simulated the RAnge Length PHantom (RALPH) [1], which enables range verification of different tissue configurations using Gafchromic film. RALPH consists of two slabs of solid water ($10\times10\times1$ cm^3), in between which a slab of interchangeable material ($10\times10\times0.5$ cm^3) is located. This configuration is followed by two $5\times10\times10$ cm^3 slabs of solid water, with Gafchromic film placed in between (Fig. 1(a)). The interchangeable slab was replaced by 3D-printed slabs of Acrylonitrile Butadiene Styrene (ABS), a common 3D-printing filament. The slabs were simulated either as homogeneous blocks with mass density according to the infill percentage (20%, 50% and 80%) or considering realistic geometries that mimic the honeycomb pattern and different printing directions (Fig. 1(b)). The honeycomb pattern was mimicked through air cylinders built within the slab of ABS (Fig. 1(c)). The diameter of the cylinders was of 0.1 cm, 0.2 cm or 0.4 cm, corresponding to 80%, 50% and 20% infill, respectively. The length of the cylinders was such that a 0.2 mm surrounding solid shell of ABS was present, representing the number of outline solid layers used during printing. The air cylinders were positioned in the *x*, *y* or *z* directions – cylinders positioned in the *z*-direction

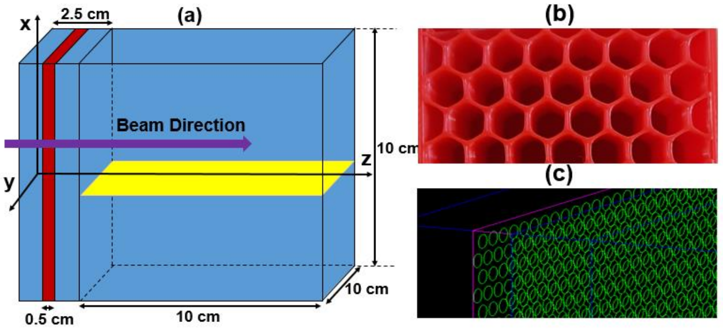

Figure 1: *Schematics of RALPH: the blue slabs are solid water, the red slab is the interchangeable material (ABS) and the yellow geometry is Gafchromic film (a). Representation of a real slab 3D-printed using the honeycomb pattern (b) and its representation in GATE (c).*

were parallel to the beam direction. A 4×4 cm^2 field of 150 MeV protons was simulated using 5×10^8 primary particles. The dose in the Gafchromic film was scored in 2D with a resolution of $0.1\times0.02\times0.02$ cm^3.

Results

The range of the proton beam, the width of the Bragg peak and the 2D dose distributions were evaluated for the various testing scenarios and are shown in Fig. 2 (a), (b) and (c), respectively.

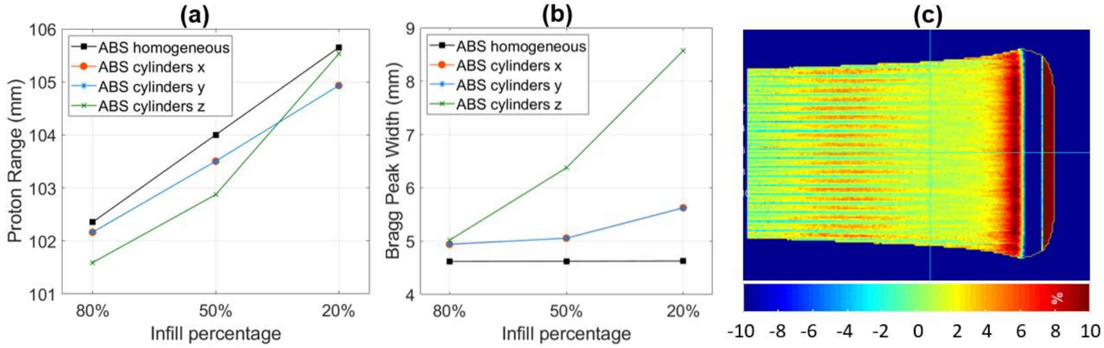

Figure 2: *Range (a) and width (b) of the depth dose curves for the studied configurations. Example of a 2D local map difference between the patterned and homogeneous cases for 50% infill (c).*

Discussion & Conclusions

Proton interactions resulted in different dose deposition shapes when considering the patterned versus homogeneous case as well as the different printing directions. The range was the highest and the width was the smallest for the homogeneous slabs, for all infill percentages. When the printing direction was perpendicular to the beam direction, differences of 0.2 mm to 0.7 mm in range, and of 0.3 mm to 1 mm in width were found in comparison to the homogeneous scenario. These differences increased with decreasing infill percentage. No differences were observed between the x and y directions, as the effect of the rotation of cylinders around the z axis cancels out when the dose is integrated. Larger differences were found between the homogeneous case and cylinders parallel to the beam direction (up to 1 mm in range and 4 mm in width). For 20% infill, due to the large radius of each cylinder and the small spacing in between them, the protons interacted mainly with air. The range was similar to the range of the corresponding homogenous case, but the width was 4 mm larger, reflecting the energy spread that originated from scattering within the geometry. To conclude, we developed a MC-based framework able to simulate range measurements of realistic 3D-printed materials. This framework will support the optimisation of 3D-printing settings for the development of tissue-equivalent materials. Further work is needed to experimentally validate current findings as well as further simulation work to mimic other 3D-printed infill patterns and imperfections.

References

[1] Cook H *et al*. Development of a heterogeneous phantom to measure range in clinical proton therapy beams. *Physica Medica 2021 (In Press).*

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