A Novel 3D-Printing Process for a Tissue-Equivalent Phantom for Single-Isocenter Multi-Target Stereotactic Radiosurgery

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INTRODUCTION

Stereotactic radiosurgery (SRS) is the precise delivery of a single ablative dose of radiation to one or more small well-defined targets. Non-coplanar single-isocenter multi-target (SIMT) volumetric modulated arc therapy (VMAT) techniques are becoming the standard of care for cranial SRS on standard linacs, minimising intrafraction motion through faster treatment times compared to multi-isocentre techniques, and improving dose conformity to target lesions[1,2].

The added complexity of SIMT SRS necessitates a comprehensive and accurate program for both commissioning and pre-treatment dose verification[3]. An ideal phantom for SIMT SRS commissioning, end-to-end (E2E) testing and patient specific quality assurance (PSQA) would (1) be radiologically tissue equivalent, (2) replicate the size/shape of a patient's head, (3) include the ability to accurately localise targets[4], (4) enable measurement of any target volume regardless of its position relative to the isocentre, (5) house multiple detector types for both point dose and 2D planar dose distribution information[5,6], (6) allow couch rotations, and (7) enable image based alignment of the phantom.

While there are commercially available phantoms for SIMT SRS QA, they have a high associated cost, are usually not tissue-equivalent, and utilise detectors that require correction factors[7,8].

AIM

The aims of this project were to (1) develop and apply a process to optimise 3D-printing specifically for tissue-equivalent small-field dosimetry phantoms and, (2) design and test a cost-effective, purpose-built 3D-printed phantom for SIMT SRS dose verification.

METHODS

Radiological tissue equivalence was optimised by varying PLA infill density (83, 90 and 95%), matching depth-dose ($PDD_{15,5}$) and output factor measurements in PLA to Plastic Water DT (PW) for photon energies 6X, 6FFF and 10FFF and field sizes 4x4, 2x2 and 1x1 cm^2. Phantom validation involved static-gantry and fixed field arc deliveries utilising the IBA CC01 ion chamber. Nine non-coplanar SIMT SRS VMAT plans consisting of two co-axial identical spherical targets at equal off-axis distances were measured using EBT4 film and validated against off-axis CC01 measurements with dedicated 3D-printed off-axis ion chamber inserts. Measurements were measured three times to mitigate uncertainty.

A customised dosimetry phantom was constructed with 3D printed Polylactic Acid (PLA), designed as a 20 cm diameter sphere to give a simple representation of a patient's head and to ensure the same pathlength for isocentric setups for non-coplanar arc deliveries (Fig. 1). The phantom comprises multiple 3D-printed components, with an inter-changeable detector insert (ionisation chamber or Gafchromic EBT4 film). Four spherical air cavities (4 mm diameter) were built into the phantom to facilitate image-based phantom setup.

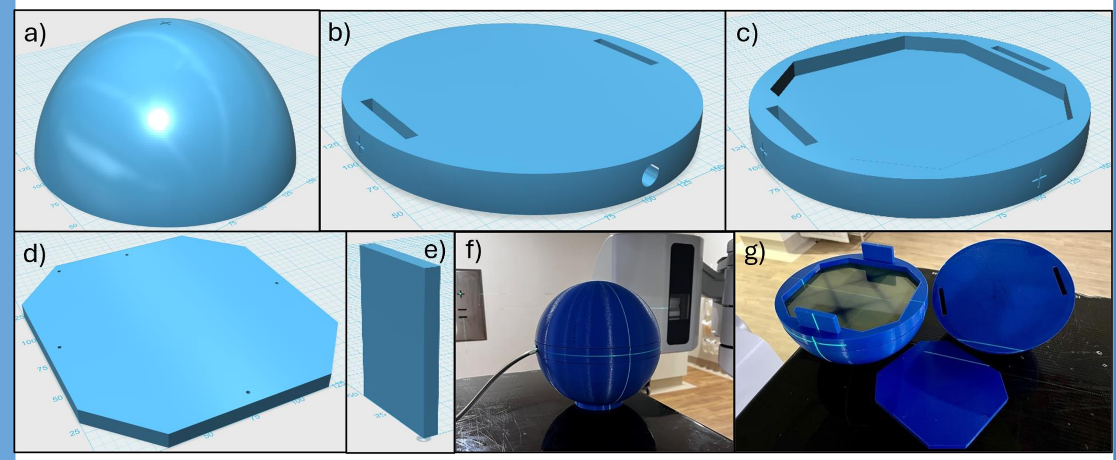

Fig. 1: Spherical phantom including a) top/bottom hemisphere, b) ion chamber insert, c) film insert, d) film insert lid, and e) internal rods. The phantom with the ion chamber insert and film insert are shown in f) and g), respectively.

Measurements were performed on a Varian TrueBeam Edge linac, equipped with 120 leaf HDMLCs and a Varian PerfectPitch[TM] 6DOF couch. Plans were calculated in the Eclipse TPS v18.1 using the AcurosXB (AXB) dose-to-medium algorithm with a 1 mm calculation grid size. Film analysis was performed using an in-house film dosimetry software package developed at Memorial Sloan Kettering Cancer Center, with a triple-channel dosimetry protocol within FilmQA Pro 2016 software (Ashland, Wayne, NJ) to generate film dose distributions.

RESULTS

Figure 2 shows the PDD dose difference (%) of PLA relative to PW as a function of infill density for all field sizes and energies in a block phantom geometry. PDD data was the metric of choice for PLA optimisation, with closest agreement to PW observed for 90% infill density.

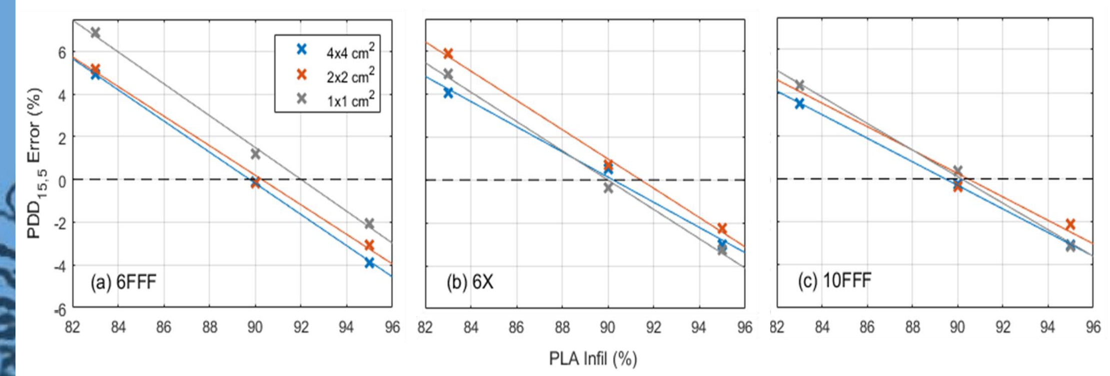

Fig. 2: $PDD_{15,5}$ dose difference (%) between PLA infill densities and PW.

Dose measurement for static-gantry fields in the phantom, 3D-printed at 90% infill density, agreed with PW measured doses to within ±1%[9], while the fixed field arc measurements agreed with TPS doses to within ±2% for all energies and field sizes[5].

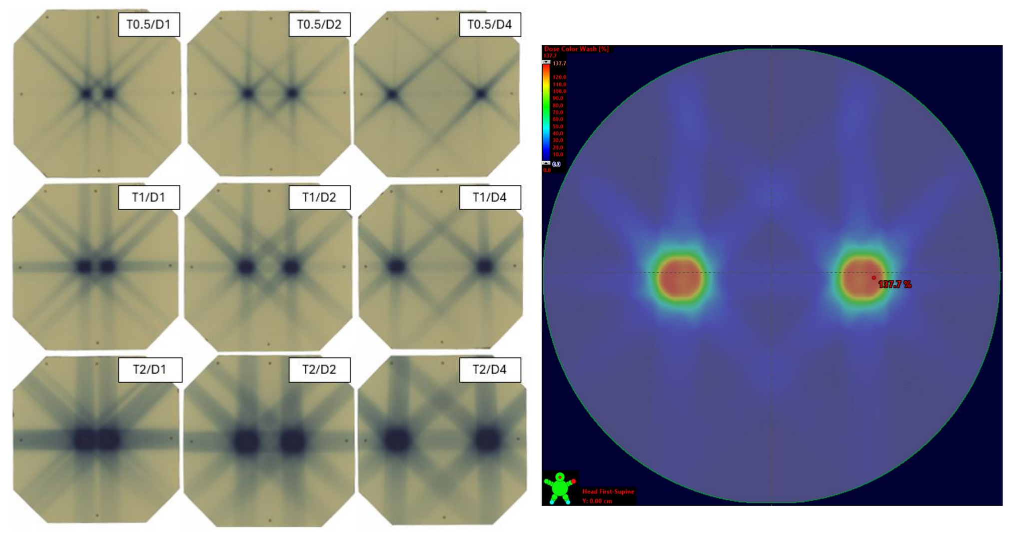

Fig. 3: Film measurements from SIMT SRS plans (left). "T" represents the target size (cm), while "D" represents the distance of each target off-axis (cm). The T2D4 TPS dose distribution for the coronal plane (right).

The SIMT SRS VMAT film-measured dose distributions compared to the TPS dose planes (Fig. 3) yielded a mean gamma pass rate (3%/1 mm) of 96.2% (range: 82.1-100%). Dose difference distributions for each plan were evaluated using the average dose within a region of interest defined by a 50% isodose threshold relative to the TPS maximum dose (Fig 4). The gamma analysis and dose difference distributions are tabulated in Table 1.

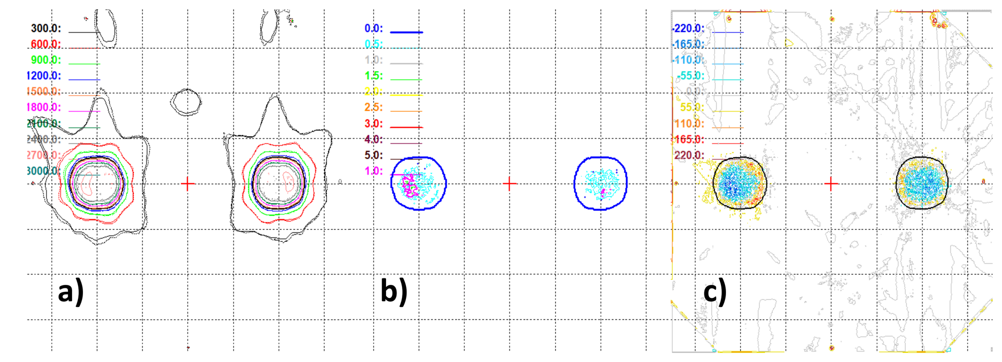

Fig. 4: Example of the T2D4 film analysis, including a) the overlayed film (dash line) and TPS (solid line) dose distributions (cGy), b) the 3%/1 mm gamma analysis, and c) the dose difference distribution (cGy).

SIMT SRS Plans T: Target size (cm) D: off-axis distance (cm)	GPR (%) 5%/1 mm Threshold: 50%	GPR (%) 3%/1 mm Threshold: 50%	Ave % Diff in ROI Left Target	Ave % Diff in ROI Right Target
T0.5 D1	97.3 ± 3.6	96.7 ± 3.8	6.2 ± 1.9	6.8 ± 2.1
T0.5 D2	98.8 ± 1.6	98.1 ± 2.2	5.3 ± 1.7	4.6 ± 1.1
T0.5 D4	100 ± 0.0	99.9 ± 0.1	2.5 ± 1.8	2.3 ± 1.4
T1 D1	100 ± 0.0	100 ± 0.0	2.9 ± 0.9	2.2 ± 0.8
T1 D2	100 ± 0.0	99.9 ± 0.0	2.0 ± 0.9	1.1 ± 0.9
T1 D4	98.0 ± 1.6	93.5 ± 3.8	-0.3 ± 1.2	-0.6 ± 1.1
T2 D1	99.5 ± 0.7	96.7 ± 4.3	0.2 ± 1.6*	
T2 D2	99.4 ± 0.8	98.6 ± 1.3	-0.7 ± 0.9	-0.2 ± 0.8
T2 D4	90.2 ± 10.0	82.1 ± 14.0	-1.8 ± 2.3	-2.4 ± 3.5

Table 1: Film gamma pass rate and in target dose difference distributions for the SIMT SRS plans compared to TPS dose. Results are displayed as a mean ± standard deviation.*Combined target average % diff reported.

The CC01 ion chamber SIMT SRS validation results tabulated in Table 2 show agreement to within ±3% of the TPS calculated mean CC01 dose. The TPS dose is used as the reference, hence the negative values indicate a lower CC01 measured dose in the spherical phantom.

SIMT SRS Plans T: Target size (cm) D: off-axis distance (cm)	CC01 Dose Error (%) Left Target	CC01 Dose Error (%) Right Target
T1 D1	-0.4 ± 0.1	-0.3 ± 0.3
T1 D2	-2.3 ± 0.1	-2.5 ± 0.2
T1 D4	-2.9 ± 0.1	-2.4 ± 0.6
T2 D1	-0.5 ± 0.0	-0.1 ± 0.1
T2 D2	-1.5 ± 0.1	-1.5 ± 0.1
T2 D4	-2.3 ± 0.1	-2.2 ± 0.3

Table 2: Dose differences between CC01 measurements in the spherical phantom compared to the TPS calculated mean CC01 dose. Due to the CC01 cavity size, only plans with 1 and 2 cm targets were utilised for ion chamber SIMT validation.

KEY FINDINGS

- This is the **first study** that optimises 3D printer parameters for tissue equivalence in small field dosimetry, and the only radiologically tissue-equivalent 3D printed phantom designed specifically for SIMT SRS commissioning, E2E testing and PSQA. The phantom is also suitable for SRS remote auditing and site credentialing[10].
- Phantom design allows customisation for a range of detector types and measurement configurations and can be readily manufactured at centers with access to standard 3D-printing facilities.
- With a cost-to-print of approximately $150 USD, the cost-effectiveness makes the phantom well suited for centres implementing or using SIMT SRS in settings with limited financial or resource capacity.

CONCLUSION

This study demonstrated a novel 3D-printing process for a cost-effective, radiological tissue-equivalent phantom for SIMT SRS dose verification, representing a practical and accessible tool for SIMT SRS applications.

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