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FULL PAPER

Adaptation and validation of a commercial head phantom for cranial radiosurgery dosimetry end-to-end audit

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Objective: To adapt and validate an anthropomorphic head phantom for use in a cranial radiosurgery audit.

Methods: Two bespoke inserts were produced for the phantom: one for providing the target and organ at risk for delineation and the other for performing dose measurements. The inserts were tested to assess their positional accuracy. A basic treatment plan dose verification with an ionization chamber was performed to establish a baseline accuracy for the phantom and beam model. The phantom and inserts were then used to perform dose verification measurements of a radiosurgery plan. The dose was measured with alanine pellets, EBT extended dose film and a plastic scintillation detector (PSD).

Results: Both inserts showed reproducible positioning (± 0.5 mm) and good positional agreement between them (± 0.6 mm). The basic treatment plan measurements showed agreement to the treatment planning

system (TPS) within 0.5%. Repeated film measurements showed consistent gamma passing rates with good agreement to the TPS. For 2%-2 mm global gamma, the mean passing rate was 96.7% and the variation in passing rates did not exceed 2.1%. The alanine pellets and PSD showed good agreement with the TPS (-0.1% and 0.3% dose difference in the target) and good agreement with each other (within 1%).

Conclusion: The adaptations to the phantom showed acceptable accuracies. The presence of alanine and PSD do not affect film measurements significantly, enabling simultaneous measurements by all three detectors.

Advances in knowledge: A novel method for thorough end-to-end test of radiosurgery, with capability to incorporate all steps of the clinical pathway in a time-efficient and reproducible manner, suitable for a national audit.

INTRODUCTION

The use of stereotactic radiosurgery (SRS) has rapidly increased since its inception in 1951.² There are now several manufacturers that offer commercial solutions for delivering SRS and typically such treatments are delivered by either a Gamma Knife unit, a CyberKnife robotic radiosurgery system or a linear accelerator-based system.³ It is necessary that all radiotherapy practices are subject to appropriate quality assurance procedures, including regular quality control testing and independent dosimetry audit, to minimize potential errors in treatment delivery that can lead to clinical complications.^{4,5} This is especially the case for SRS where a very high dose is delivered in only a single fraction, meaning an error cannot be mitigated in a subsequent fraction. It has previously been argued that simple homogeneous and geometric phantoms are not ideal for assessing the dosimetric and geometric accuracies of

modern radiotherapy techniques as they are not representative of patient-like conditions.⁶ There are numerous examples where anthropomorphic phantoms have been utilized for complex radiotherapy treatment quality assurance, audits and trials.⁷⁻¹⁰

In this study, we present the adaptation of a commercial anthropomorphic phantom for the novel use of three simultaneous detectors, with the purpose of employing it for a radiosurgery dosimetry audit. The methodology utilized was guided by the results of a recent survey on the current practice for cranial SRS in the UK.¹ This indicated that single brain metastatic lesions of volumes ranging from 1 to 20 cm³ are one of the most commonly treated indications. The survey also highlighted that quality assurance programs should provide confidence not only in the dose delivered but also the location and shape of the dose

distribution delivered, as SRS is often prescribed to irregularly shaped targets near or even within an organ at risk (OAR).

The goal of the adaptation was to combine a close representation of a typical radiosurgical patient case, with a design capable of simultaneous measurements with a number of previously characterized detectors, suitable for SRS dose measurement. These were a commercial plastic scintillation detector (PSD), Exradin W1;¹¹ a new commercially available radiochromic film, EBT extended dose (EBT-XD);¹² and alanine pellets.¹³ The validation of this phantom and detectors combination included verification that the different systems did not adversely affect one another when making simultaneous measurements.

METHODS AND MATERIALS

STE₂EV is a commercially available anthropomorphic phantom (CIRS, Norfolk, VI) which has been designed with a range of materials to simulate tissue electron densities (Figure 1). The phantom contains bone and soft-tissue structures, as well as teeth and air gaps to reflect realistic anatomy. These tissue inhomogeneities are an essential feature in assessing the accuracy of convolution-based planning. The phantom design allows the insertion of interchangeable cuboid inserts in the centre of the brain and the insertion of radiation detectors through two parallel cylindrical access cavities that run superior to inferior through the phantom connecting the neck to the brain. The two cylindrical access cavities are 3 cm apart, centre to centre. The anterior cavity is aligned with the trachea and the posterior cavity is aligned with the spinal cord.

Two interchangeable bespoke cuboid inserts were developed for the brain cavity of the phantom. The first, the target insert, was modelled on real anatomical structures from clinical CT to simulate a patient as closely as possible. The insert is a three-dimensional printed cube made of proprietary resin that contains two liquid-fillable structures: one irregularly shaped “target” structure [planning target volume (PTV)] designed to simulate a centrally located brain metastasis of typical size ($\sim 8\text{ cm}^3$) and another OAR structure in the shape and size of the brainstem and thalamus of the brain (Figure 2a). The shape of the PTV was carefully designed to simulate various beam-shaping issues that are often met in SRS planning. The two

structures are aligned and centred with the cylindrical access cavities. The posterior surface of the PTV structure is approximately 1 cm away from the anterior surface of the OAR.

The second, the dosimetry insert, is made of the same material as the surrounding brain-equivalent material, obtained from the manufacturer, and was designed for multiple simultaneous dose measurements (Figure 2b). It is comprised of three cubes which, when joined together, have the same dimensions as the target insert (Figure 3). The dosimetry insert was engineered to have two planar indentations of 280- μm depth to be loaded with the film, one in the sagittal and one in the axial plane. Sections through these are shown in Figure 2b. The axial film is positioned such that it bisects the target structure in the superior-to-inferior direction. The sagittal film is positioned superior and perpendicular to the axial film, such that it bisects the superior half of the target structure. Three small (1-mm diameter) fiducial markers have been built into each film plane (Figure 3a) that produce small indentations on each film when the insert is fully assembled. These indentations are used when aligning irradiated films to the treatment planning system (TPS)-exported dose plane to allow accurate registration during analysis.

The lower part of the insert, which sits under the axial film, allows access from the inferior direction through the cylindrical cavities of the phantom, for the placement of other radiation detectors. Two bespoke detector holders have also been manufactured to hold the PSD and a stack of four alanine pellets. They are interchangeable so that they can be used to make measurements in both cylindrical cavities. The holders were designed so that the geometric centres of the top alanine pellet and the PSD are aligned as shown in Figure 4. The goal of this alignment was to have the two measurement systems (alanine and scintillator) placed in the same interchangeable position, enabling two detectors with different sizes to produce comparable measurements.

The methodology was designed to enable accurate point measurements as well as accurate dose distribution measurements. Alanine¹⁴ and radiochromic film^{15,16} have been chosen due to their good performance in dose measurement and successful use in other previous radiotherapy dosimetry audits. The recently available EBT-XD film was preferred to the more commonly used EBT-3 film as we have previously demonstrated that it is more suitable for small-field high-dose applications, mainly due to its extended dose range and reduced lateral scanner effects.¹² Both alanine and EBT-XD film are near-water-equivalent detectors, with alanine having a small sensitive volume and the film having high spatial resolution, characteristics considered ideal for SRS dosimetry. The Exradin W1 PSD is another novel detector with the same attractive characteristics, making it suitable for SRS-type small field measurements. The chosen methodology enables us to assess the performance of this detector in SRS against the TPS calculated dose but also against alanine which is a reference dosimeter and an established audit dosimeter. Alanine has been used for the national intensity-modulated radiation therapy audit,¹⁷ the initial tests in the national volumetric modulated arc therapy audit to validate the array,¹⁸ as the absolute dosimeter in the national lung

Figure 1. Annotated picture of the STE₂EV phantom with the inserts and detectors used in this work.

Figure 2. (a, b) Sections of the phantom through axial, coronal and sagittal planes with the target insert (a) and the dosimetry insert (b) inside the cavity.

stereotactic ablative radiotherapy audit¹⁹ and in the current national flattening filter-free audit.²⁰ It is directly traceable to the national primary standard and thus is suitable to confirm

measurements made with other detectors, as a reference dose-meter. All detectors chosen are comparable in size or smaller than the field sizes typically used for radiosurgery. Assuming

Figure 3. Successive images of the different parts of the dosimetry insert being put together. (a) All parts of the insert and the three fiducial markers of each film plane are indicated by a circle. (b–d) The insert being assembled. (e) The dosimetry insert fitted into the phantom and (f) the film in the insert after irradiation.

Figure 4. Schematic representation of the sagittal plane through the middle of the phantom showing all detectors on the planning target volume (PTV) and organ at risk (OAR). The scintillator positions are superimposed on the interchangeable alanine pellet positions. Both are cylindrical detectors—dimensions of the scintillator: 3-mm length $\times$ 1-mm diameter; dimensions of the pellets: 2.5-mm length $\times$ 5-mm diameter.

a relatively homogeneous dose distribution in the volume of these detectors, they are expected to generate reliable measurements. For measurements in the OAR, larger deviations were expected due to lower absolute doses and steeper dose gradients.

The Exradin W1 PSD was calibrated for its stem effect (Cherenkov light ratio) and dose-to-water (GAIN) correction factors following the manufacturer's recommendations²¹ in a 40 $\times$ 40- and 10 $\times$ 10 -cm field, respectively, with the latter made against a PTW 0.125-cm³ 31010 Semiflex chamber with a traceable calibration to the National Physical Laboratory, Teddington, UK. In a previous characterization conducted for the Exradin W1 PSD,¹¹ a series of tests were conducted to account for the detector uncertainties in SRS measurements, such as for angular dependence and Cherenkov light ratio determination, and these were included in the uncertainty budget.¹¹

The calculated combined standard uncertainties (coverage factor $k = 1$) for absolute dose measurements of all detectors used in this study are shown below in Table 1.

Positioning accuracy of inserts

Five CT scans of 0.625-mm slice thickness were performed with each insert inside the phantom cavity, to produce scans with as

high spatial resolution as possible. The inserts were removed and replaced between each scan to assess the reproducibility of positioning the inserts. The CT-origin was centred for all scans using the phantom's built-in fiducials, and the CT co-ordinates of two opposite corners of the cube insert were recorded for each scan. The maximum vector distance between the CT-origins and the co-ordinates of the corners was calculated and defined as the positional reproducibility of the insert. Two additional CT scans were performed with the PSD and alanine pellets switched between the two phantom cavities to assess whether their superimposed positions were as intended (Figure 4). This was assessed by contouring the detector in each position and fusing the two scans together on iPlan® Image Fusion (BrainLAB, AG, Feldkirchen, Germany).

Basic plan dose verification with ionization chamber
A basic treatment plan was generated on the phantom using iPlan RT Dose v.4.5.3 (BrainLAB AG) to be tested for plan dose verification, in order to establish a baseline of the dosimetric accuracy of the phantom. The dose was calculated with the pencil-beam algorithm using a 2-mm calculation grid with a quoted uncertainty of ± 0.1 Gy. The treatment plan was a three-field conformal radiotherapy plan with one anterior beam at gantry angle 0° and two lateral beams at 90° and 270°.

Table 1. Detector standard uncertainties for all detectors used in this study

Detector	Standard uncertainty (%)
PTW Semiflex 31010	$\pm 0.7^a$
Individual alanine pellet at 5 Gy	$\pm 1.4^b$
Individual alanine pellet at 10 Gy	$\pm 1.0^b$
Exradin W1 plastic scintillation detector	$\pm 2.1^c$
Gafchromic EBT extended dose film	$\pm 2.5^d$

^aAs quoted on the detector's National Physical Laboratory (NPL) calibration certificate.

^bAs provided by the NPL chemical dosimetry service.¹³

^cCalculated in a previous characterization.^{22,23}

^dCalculated in a previous characterization.¹¹

Figure 5. Dose distribution comparisons between the film-measured doses (thin lines) and the treatment planning system-calculated doses (thick lines) for the axial and the sagittal films used in the end-to-end test.

All three fields had primary jaw collimation fixed at 3×3 cm and multileaf collimation shielding the four corners to produce octagons approximating circular 3-cm fields. The plan isocentre was placed in the middle of the anterior phantom cavity, to match the position of a calibrated PTW Semiflex ionization chamber. The plan was delivered to the phantom and the measured dose for each beam was compared to the TPS-predicted mean dose for a contour structure created to match the ionization chamber-sensitive volume.

Radiochromic film measurements

All EBT-XD films used in this study were from the same batch (#01081501) requiring a single calibration curve. The film measurements were performed three times to assess variations of the measurements. A measurement was conducted with the film only inside the phantom, and it was repeated twice with the other detectors present, in order to assess the effect of any perturbations caused by the presence of alanine and PSD on the film. In the absence of the film and alanine pellets, water-equivalent rods were used to fill the cylindrical cavities. The methodology used for the film analysis in this work was similar to that presented in a previous study with Gafchromic EBT-XD film.¹² The films were scanned on an EPSON Expression 11000XL (EPSON, America, Inc., Long Beach, CA) scanner at 96 d.p.i. (0.265-mm resolution) in the transmission mode with no corrections applied and were analysed on FilmQAPro (Ashland ISP Advanced Materials, NJ). They were scanned consistently in the landscape orientation 3 days after exposure to allow for post-irradiation darkening to occur. The films were always kept together in a controlled environment and were handled with latex gloves. A glass compression plate was used during the scans to keep the films flat on the scanner.²⁴ High-resolution (1 mm grid) predicted dose planes were exported from the TPS for comparison with the 48-bit images of digitized films. A selection of gamma passing rates²⁵ suitable for SRS plan analysis was chosen. These include both local and global gamma criteria to highlight the impact of agreement in the low-dose regions of the dose map distributions. The distance-to-agreement parameter of the gamma criteria used was always kept <2 mm, as distances above that are considered unacceptable tolerances for SRS delivery. Similarly, the dose-difference parameter was varied between 2% and 5% to be representative of acceptable tolerances in SRS whilst accounting for the steep dose gradients present. The gamma passing rates used were collected using the red colour channel with triple-channel dosimetry correction²⁶ for the regions shown in Figure 5 (50×60 mm for axial and 70×40 mm for sagittal), with a cut-off threshold for doses <200 cGy to remove areas of low signal and high noise from the analysis.

End-to-end validation test

The phantom, inserts and detectors were tested for their suitability in performing an end-to-end⁵ dosimetry test for SRS. The phantom was immobilized in a thermoplastic mask used for radiotherapy treatment and CT scanned with both inserts in the cavity. The two scans were then imported into iPlan where they were fused; the target, brainstem and detectors were contoured and a seven-field intensity-modulated radiation therapy plan was generated and calculated using the pencil-beam algorithm.

The plan was delivered on a TrueBeamTM STx Linac (Varian, Palo Alto, CA) with ExacTrac[®] (BrainLAB AG). The phantom position was verified three times during each delivery, one for each couch angle, using orthogonal radiographic images. The phantom position was found to be accurate within 0.7 mm, and therefore no shifts were applied. Measured point doses and dose planes were compared with TPS-predicted doses and planes.

RESULTS

Positioning accuracy of inserts

The vector distances from the CT-origin for the two points of the dosimetry insert were found to range from 53.51–53.79 mm for Point 1 and from 74.18–74.61 mm for Point 2. For the target insert, the two distances ranged from 53.47 to 53.87 mm and from 74.06 to 74.46 mm, respectively. From the measurements, the maximum deviation in position was <0.5 mm for both inserts, and the positional agreement between the two inserts was found to be better than 0.6 mm. This suggests that the uncertainty in positioning is of the order of the CT scan resolution of approximately 1 mm. The detector holders showed reproducible placement of the PSD and alanine detectors and confirmed that the intended relative positions were as designed and shown in Figure 4. This analysis was limited to a qualitative assessment as any quantification of the PSD position was not possible due to the small and water-equivalent sensitive volume of the detector that was difficult to visualize on the CT scans.

Basic plan dose verification with ionization chamber

Table 2 shows the Semiflex ionization chamber measurements for the plan dose verification of the basic three-field plan. The percentage difference for each beam and the overall difference were within 0.5%, suggesting an acceptable phantom accuracy.

Radiochromic film measurements

High levels of agreement were found between the film and TPS, whether alanine or PSD were in place or not. For all global criteria used (Table 3), $>93.2\%$ of pixels were in agreement, regardless of which other detectors were present in the phantom. Any differences seen between local and global gamma had disagreements mainly in the low-dose areas. However, these disagreements are not substantial as the results for 5%-2 mm local gamma were always $>96.1\%$.

The variation in gamma passing rates between the three pieces of film was very similar for all the criteria investigated. The maximum percentage difference was seen with the strictest criteria of 5%-1 mm local and 5%-1 mm global gamma, which was 3.8% and 3.7%, respectively.

End-to-end validation test

Table 4 shows results for the PSD and alanine measurements. The difference between measured and TPS dose was within 0.4% for the PTV and the agreement between the PSD and alanine pellet 1 was also within 0.4%. For the OAR, the differences between the measured and TPS-predicted doses were 19.8% and 18.6% for PSD and alanine pellet 1, respectively. The agreement between PSD and alanine pellet 1 in the OAR was within 1.2%. The film dose plane measurements are shown in Figure 5.

Table 2. Ionization chamber measurements for a basic three-field treatment plan

Beam name	Measured dose (in cGy)	Predicted dose (in cGy)	Percentage difference (in %)
Left lateral	50.7	50.5	0.4
Anterior	101.2	100.7	0.5
Right lateral	49.8	49.6	0.5
Total	201.7	200.8	0.5

DISCUSSION

As the phantom and inserts are intended for performing end-to-end tests in SRS, it is imperative that the positional uncertainty of the inserts is as low as possible. A previous survey found that the majority of SRS centres in the UK reported positional accuracies <1 mm for SRS delivery.¹ Considering the engineering tolerances allowed to facilitate insertion and removal of the two inserts inside the phantom, the submillimetre variations found are considered acceptable.

The agreement between film and TPS for the three films used in this study showed mean passing rates of 96.7% for 2%-2 mm global gamma. This shows equivalent agreement with measurements previously performed in a simple homogeneous phantom.¹² The results presented in this study also demonstrate similar levels of agreement with the TPS to other studies that also used anthropomorphic phantoms.^{8,16,27} Most importantly, the film measurements show a high degree of consistency which is essential if the methodology is to be employed for audit purposes. The high agreement with the TPS and consistency in measurement suggests that this is an appropriate phantom design and film methodology to be used for an end-to-end audit.

The PSD showed very good agreement with the TPS and the first alanine pellet. The agreement between the two detectors in the target was within 0.4%, demonstrating the potential of positioning two detectors of different geometries in the same area to compare their measurements. The results also suggest that the Exradin W1 PSD could be a suitable detector for end-to-end audits.

The measurements performed in the brainstem show larger differences from TPS calculated doses than the measurements in the target. This is due to the measurement being performed in

a region with a high dose gradient, where a small positional deviation results in a large dose difference. The detector signal measured is also much lower than the detector signal measured in the target which hence produces larger uncertainties in the relative measurement. Despite the above, the absolute difference between the measured and predicted doses is at low levels of 8–9 cGy. Also, the difference between the alanine pellet in the brainstem and the PSD is within 1%, giving more confidence to the measurement. Moreover, the two film measurements performed that sit immediately superior to the two detectors also show that the dose measured in the brainstem is slightly higher than the TPS predicted dose. This therefore confirms that the measurements of the three independent systems provide consistent results, even in out-of-field regions where the TPS calculation algorithm may be less accurate.²⁸

The perturbation of alanine and PSD on the sagittal film plane was expected to be very low due to the near-water-equivalent density of the two detectors. Furthermore, the small volume of the two detectors, relative to the large area of the film, would only potentially affect a small number of pixels, which would be reflected in a very small change in gamma passing rates. The gamma passing rate differences observed between the three exposures are mostly attributed to dose differences in the low-dose regions. These must therefore be related to film measurement variations or treatment delivery variations but not detector perturbation. The results confirm that the differences seen are very low as hypothesized.

The phantom and inserts used enabled a thorough test of all aspects of the treatment protocol in place for SRS. The immobilization system, CT scan and scanning protocol, import of images into TPS, fusion of two sets of scans, TPS accuracy, export of images on the treatment platform, pre-treatment

Table 3. Gamma passing rates for EBT-extended dose axial film measurements with and without the plastic scintillation detector (PSD)/alanine abutting the film plane

Detectors placed in the phantom	Local gamma				Global gamma			
	5%-2 mm	3%-2 mm	2%-2 mm	5%-1 mm	5%-2 mm	3%-2 mm	2%-2 mm	5%-1 mm
Film only	97.1	87.1	73.3	73.6	99.8	96.4	95.9	93.2
Film with PSD	96.1	88	76	70.4	100	99.8	98	96.9
Film with alanine	96.9	87.9	75.1	69.8	100	97.4	96.2	95.4

Table 4. Measurements in the target and organ at risk (OAR) compared with treatment planning system (TPS)-predicted doses

Detector location	Detector used	Measured dose (in cGy)	TPS predicted dose (in cGy)	Percentage difference (in %)
Detectors in the PTV	PSD	2605.7	2598.0	0.3
	Pellet 1	2595.6	2598.0	−0.1
	Pellet 2	2598.4	2595.0	0.1
	Pellet 3	2604.4	2595.0	0.4
	Pellet 4	2613.6	2604.0	0.4
Detectors in the OAR	PSD	51.5	43.0	19.8
	Pellet 1	51.0	43.0	18.6

PSD, plastic scintillation detector ; PTV, planning target volume.

imaging for precise positioning and finally dosimetric and geometric accuracy of the treatment delivery were all tested. Although intrafractional motion cannot be tested by a stationary phantom, the inclusion of the immobilization system in the end-to-end chain allows for testing the reproducibility of the phantom's position between the CT scan and treatment delivery with or without the aid of on-board imaging. It should also be noted that due to the limited visibility of the phantom on MRI scans, it was not possible to incorporate this in the end-to-end chain.

CONCLUSION

In this work, we have presented the adaptation of a commercial anthropomorphic phantom with suitably designed inserts, to image and irradiate, during an end-to-end dosimetry audit of SRS. We have demonstrated that the inserts produced have reproducible positioning inside the phantom, and they can be utilized for end-to-end tests to provide accurate and repeatable measurements. We have also showed that with the adopted

methodology, it is possible to achieve high agreement and repeatability between TPS and the three detectors used in the phantom (EBT-XD film, alanine pellets and the Exradin W1 PSD). The use of all detectors simultaneously inside the phantom does not produce any large perturbations and is therefore a suitable and time-saving methodology. The work has demonstrated a novel combination of three detectors for simultaneous measurement in an anthropomorphic phantom which create a suitable phantom-detector system and methodology for an end-to-end SRS dosimetry audit.

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