End-to-End Quality Assurance of Stereotactic Radiation Therapy Using an Anthropomorphic Head Phantom

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Abstract. In the clinic, routine quality assurance tests ensure the proper functioning of each individual aspect of a radiation therapy treatment delivery. However, these tests may not guarantee an accurate treatment delivery. In this work, we present the design and application of a head phantom (using 3D printing technology) developed for end-to-end quality assurance of a stereotactic radiation therapy treatment for brain metastases, coupled with inserts for ion chamber, and film and gel dosimeters. The head phantom was subjected to the entire clinical workflow, with each stage of the process being performed by the appropriate clinical personnel to ensure that this quality assurance test mimics the clinical scenario.

1. Introduction

Approximately 20-40% of all patients with cancer will develop brain metastases at some point in their life [1], with many of these patients suffering from multiple brain lesions [2]. One option for the treatment of this type of cancer is fractionated stereotactic radiation therapy (FSRT) using a linear accelerator (linac) [3]. Due to the high complexity of these deliveries and the small targets involved, it is crucial to ensure the geometric and dosimetric accuracy of the delivery. While routine quality assurance (QA) tests are performed to verify that treatment machines and planning systems are working properly, this does not inherently mean that the overall treatment process and delivery is accurate. For this reason, initiating routine end-to-end (E2E) QA would be useful to validate the entire treatment process [4,5].

In this work, we performed an in-house E2E QA test of a FSRT brain metastases volumetric modulated arc therapy (VMAT) radiation therapy treatment by creating an anthropomorphic head phantom, handing it over to the radiation therapists, and verifying the entire process (from CT simulation, through patient setup, to radiation delivery) by measuring the overall dosimetric and geometric accuracy using multiple dosimeters.

2. Methods

2.1. Phantom Design

An anthropomorphic head phantom was created and adapted so that it could accommodate a variety of dosimeters, while also approximating the densities and CT numbers of a human head. To create the phantom, a 3D model of the Rando phantom skull was first generated. To accommodate dosimeters, a
A cylindrical cavity (diameter = 7.0 cm, length = 12.6 cm) was added to the skull, running in-line with the neck (Figure 1). The skull model was post-processed to ensure that the brain region was watertight in order to replicate the radiological properties of a human brain. The skull model was 3D printed using a high density iron-filled PLA (3D Printing Canada, Hamilton, Ontario) using a Prusa i3 MK3 3D printer (Prusa Research, Prague, Czech Republic) at 100% infill. The skull was filled with water and sealed. Polydoh moldable plastic (Materialix, Jaslo, Poland) was used to create some portions of the phantom simulating soft tissue.

2.2. Dosimetry Systems and Phantom Inserts

A cylindrical insert (diameter = 7.0 cm, length = 14.0 cm) was 3D printed (100% infill) using PLA (Prusa Research) with a 10 cm deep channel in the centre for an ion chamber. A Capintec PR-05P 0.07 cc thimble ionization chamber (Capintec, Ramsey, NJ) was used in this work. The chamber insert was placed in the head phantom, and the ion chamber was positioned in the centre of the insert.

Figure 1. (a) The 3D printed skull at the midway point of the print, showing the cylindrical cavity and hollow brain. (b) The head phantom, placed on a neck rest on the linac couch. (c) Eclipse treatment planning system screen capture showing the brain region (no cavity/insert visible) to highlight the contoured regions. (d) The film insert, showing the three irradiated film plane PTVs and the fiducial points on each film. (e) An FXG gel dosimeter after irradiation, showing the irradiated dose distribution and optical fiducial markings.

A cylindrical insert for film (Gafchromic EBT3, International Specialty Products, Wayne, NJ) was 3D printed (PLA, 100 % infill) in four parts to allow for three films to be placed in three separate planes. Metal BBs were implanted in the insert sections at the surface of each 3D printed film plane and marker dots coincident with the BBs were marked on the film to facilitate registration. Film readout was performed using our in-house point scanner and scans were acquired 24 hours after irradiation at 0.6 mm resolution. Analysis was performed using 3D Slicer and the Film Dosimetry Analysis slicelet [6].
The third phantom insert was a gel dosimeter jar. Both leuco crystal violet (LCV) micelle gel dosimeters [7] and Fricke-xylenol orange-gelatin (FXG) gel dosimeters [8] were used in this work. All gel dosimeters were scanned using a Vista Optical CT Scanner (ModusQA, London, ON) pre-irradiation, and 30 mins post-irradiation. Analysis of the gel dosimeter data was performed using 3D Slicer and the Gel Dosimetry Analysis slicelet [9].

2.3. CT Simulation, Treatment Planning, and Delivery
To best replicate the clinical scenario, the head phantom was handed over to the radiation therapy team and was CT scanned according to our clinic’s brain VMAT FSRT policy. The phantom was placed in a neck rest and a thermoplastic mask was used for immobilization on a type-S overlay head and neck board (Civco Medical Solutions, Coralville, IA). Separate CT scans were acquired for each of the dosimeter inserts using a Philips Brilliance Big Bore CT scanner (Philips Medical Systems, Cleveland, OH) with a tube energy of 120 kV and a slice thickness of 1 mm.

Treatment planning was performed by the Physics team using Eclipse (Varian Medical Systems, Palo Alto, CA). Four spherical brain metastases were defined: one 2 cm diameter metastasis and three 1 cm diameter metastases. Planning target volumes (PTVs) were generated following our clinical policy. Two coplanar 6 MV clockwise/counterclockwise arcs were used, followed by a third 6 MV arc, involving a couch rotation of 45°. Planning was performed so that 100% of the prescription dose covered at least 95% of each of the 4 PTVs. An EVAL50 structure was also generated, consisting of all four PTVs plus a 0.8 cm margin in the superior/inferior direction and 1.5 cm everywhere else. As per clinical protocol, the calculated 50% dose cloud was contained within this structure.

To fully assess the image-guided radiation therapy (IGRT) treatment process for a VMAT FSRT treatment, our clinical radiation therapy team performed the setup and delivery of the treatment. Each type of dosimeter was irradiated on a different day, meaning that there were three independent setups and radiation therapist teams who assisted. Radiation therapists first set-up the head phantom according to the clinical protocol. Next, they acquired a cone beam CT scan and a 3D-3D match was performed within a region of interest encompassing the skull. The translational and rotational shifts were calculated and applied as needed to achieve a clinically acceptable match. Once the phantom had been shifted to the treatment position, the plan was delivered for each dosimeter.

3. Results

3.1. Phantom Design and Set-Up
The head phantom developed in this work has three distinct anatomical features: brain, soft tissue, and skull. In the phantom, the mean CT number of the water-filled brain is 10 HU, the PCL skin and soft tissue layer (while slightly variable due to pockets of air trapped between layers of PCL) is 65 HU, and the 3D printed skull has a mean CT number of 750 HU. The gel dosimeter has a mean CT number of 10 HU, while the 3D printed PLA inserts have a mean CT number of 120 HU.

CBCT imaging was performed before each delivery. The applied translational shifts were < 2 mm and the rotational shifts were < 0.5°, indicating that the initial set-ups by the radiation therapists were accurate using the setup markings on the mask.

3.2. Dosimeter to Plan Dose Analysis
As shown in Table 1, ion chamber dose measurements were within 2% of the mean dose calculated in Eclipse within the sensitive volume of the chamber. Across all film and gel fiducial based registrations, the average root mean square error (RMSE) between coincident fiducial points was < 1 mm. Film and gel dosimeters were all calibrated under standard conditions [9] so that an absolute dosimetric comparison could be made (no dose scaling was performed). Gel dosimeters were handled according to the protocols described in Olding and Schreiner (2011) [10]. In Figure 2, dose profiles across the center of each of the 4 PTVs are shown for film, FXG gel, and LCV gel. There was very good spatial agreement between the Eclipse planned dose and the calibrated film and gel measurements, however,
dosimetrically there are a few regions of disagreement in both film and gel when compared to Eclipse planned doses. Gamma comparisons for the film measurements show excellent agreement with the Eclipse planned dose at both 3%/3mm and 3%/1mm criteria (Table 2). While the calibrated film measurements agree with Eclipse planned doses for the 2 cm PTV, the 1 cm PTV peak doses are roughly 6% higher than the Eclipse dose. Dose readings in the calibrated gel measurements for both gel types are consistently low when compared to Eclipse and range from 3-6% low in peak dose ratios (Table 1). This dosimetric difference is also shown in the dose profiles in Figure 2.

**Table 1.** Dosimeter measurements vs. Eclipse. Mean dose ratio is the measurement relative to the calculated dose within the PTV.

| Dosimeter       | PTV # (Diameter) | Prescription Dose (Gy) | Mean PTV Dose Ratio (%) |
|-----------------|------------------|------------------------|-------------------------|
| Ion Chamber     |                  |                        |                         |
| Film            | 1 (2 cm)         | 6.5                    | 98.5 ± 0.5              |
|                 | 2 (1 cm)         | 2.5                    | 102 ± 2                 |
|                 | 3 (1 cm)         |                        | 106 ± 2                 |
|                 | 4 (1 cm)         |                        | 105 ± 2                 |
| FXG Gel         | 1 (2 cm)         | 2.5                    | 96 ± 3                  |
|                 | 2 (1 cm)         |                        | 94 ± 3                  |
|                 | 3 (1 cm)         |                        | 94 ± 3                  |
|                 | 4 (1 cm)         |                        | 94 ± 3                  |
| LCV Micelle Gel | 1 (2 cm)         | 13                     | 97 ± 3                  |
|                 | 2 (1 cm)         |                        | 97 ± 3                  |
|                 | 3 (1 cm)         |                        | 96 ± 3                  |
|                 | 4 (1 cm)         |                        | 96 ± 3                  |

**Table 2.** Gamma pass rates for film and gel dosimeters performed using two different sets of comparison criteria: 3%/3mm and 3%/1mm.

| Dosimeter       | Comparison Region (PTV # in film plane) | Gamma Pass Rate (3%/3mm) | Gamma Pass Rate (3%/1mm) |
|-----------------|----------------------------------------|--------------------------|--------------------------|
| Film            | Plane A (1)                             | 100 %                    | 98.9 %                   |
|                 | Plane B (2 & 4)                         | 100 %                    | 98.5 %                   |
|                 | Plane C (3)                             | 100 %                    | 93.3 %                   |
| FXG Gel         | EVAL50                                  | 99.4 %                   | 93.6 %                   |
|                 | Entire jar                              | 99.3 %                   | 94.0 %                   |
| LCV Micelle Gel | EVAL50                                  | 97.1%                    | 50.2 %                   |
|                 | Entire jar                              | 94.6%                    | 55.6 %                   |
Figure 2. Dose profile comparisons along the dotted lines (as shown overlaid on the dose distribution) for irradiations to film, FXG gel, and LCV micelle gel. Film planes are indicated in the inset film insert diagram. Color bar ranges from 0.1 Gy to 3.2 Gy, representative of the deliveries to film and FXG gel, whereas LCV micelle gel has a maximum dose of ~17 Gy due to the different plan normalization (note the difference in the dose axes). Irradiations to each dosimeter were performed on separate days.

4. Discussion and Conclusions

The head phantom developed in this work for E2E QA closely resembles a human head, was easy for clinical staff to use at each stage of the treatment process and produced a realistic E2E QA test. The head phantom was economical to manufacture, with a materials cost of ~ $300. Using the phantom, our clinic’s radiation therapists were able to mimic the entire radiation therapy treatment process from patient CT simulation imaging, phantom set-up, CBCT imaging and alignment, to treatment delivery.

This multi-dosimeter approach allowed for verification of repeat treatment deliveries with validation in multiple dimensions. Ion chamber measurements showed excellent agreement with the planned dose delivery. Film dosimetry analysis using our in-house point scanner showed very good spatial agreement with the planned dose delivery. However, since our clinical policy dictates that the dose calculation be performed using a 2 mm dose calculation grid size, an underreporting of dose is observed when compared to our high resolution (0.6 mm) film measurements. A re-calculation using a 1 mm grid size was performed in Eclipse and the dose for each of the 1 cm PTVs increased by up to 5% (insignificant change to the peak dose to the 2 cm PTV), placing the film and Eclipse doses in excellent agreement. Gel dosimetry was geometrically accurate; however, it underreported the dose delivery due to optical light scatter issues within the optical CT scanner [11]. This discrepancy in dose is not as evident in the gamma pass rates shown in Table 2 due to the noisy nature of the optical CT gel measurements, leading to higher gamma pass rates [12].

The head phantom had some limitations, in that it lacked some bony anatomy (no spine due to the insert cavity), was unable to measure dose in the superior part of the brain using gel, and could not simulate patient motion during treatment. However, given these limitations and challenges using each dosimeter, together, all four dosimeters helped to give a full evaluation of the dose delivery.
Overall, these E2E tests helped to mimic a real patient IGRT process by employing specific clinical personnel to perform each step in the process, used multiple dosimetry systems, and ultimately provided a more complete picture of how the entire VMAT FSRT radiation therapy process is working properly to accurately deliver the planned treatment. Our results give us confidence that our clinical workflow is safe, accurate, and effective at treating small targets and sets the stage for routine E2E QA testing.

5. References

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