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Technical note

Investigating the spatial accuracy of CBCT-guided cranial radiosurgery: A phantom end-to-end test study

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ABSTRACT

Purpose: To evaluate the spatial accuracy of a frameless cone-beam computed tomography (CBCT)-guided cranial radiosurgery (SRS) using an end-to-end (E2E) phantom test methodology.
Methods and materials: Five clinical SRS plans were mapped to an acrylic phantom containing a radiochromic film. The resulting phantom-based plans (E2E plans) were delivered four times. The phantom was setup on the treatment table with intentional misalignments, and CBCT-imaging was used to align it prior to E2E plan delivery. Comparisons (global gamma analysis) of the planned and delivered dose to the film were performed using a commercial triple-channel film dosimetry software. The necessary distance-to-agreement to achieve a 95% (DTA95) gamma passing rate for a fixed 3% dose difference provided an estimate of the spatial accuracy of CBCT-guided SRS. Systematic ($\sum$) and random (σ) error components, as well as 95% confidence levels were derived for the DTA95 metric.
Results: The overall systematic spatial accuracy averaged over all tests was 1.4 mm (SD: 0.2 mm), with a corresponding 95% confidence level of 1.8 mm. The systematic (Σ) and random (σ) spatial components of the accuracy derived from the E2E tests were 0.2 mm and 0.8 mm, respectively.
Conclusions: The E2E methodology used in this study allowed an estimation of the spatial accuracy of our CBCT-guided SRS procedure. Subsequently, a PTV margin of 2.0 mm is currently used in our department.

1. Introduction

Single-dose stereotactic radiosurgery (SRS) is a well-established technique for the treatment of both benign and malignant lesions of the brain. Classically, radiosurgery has relied on an invasive head frame for patient immobilization and target localization [1]. In recent years, the use of image-guided radiotherapy (IGRT) systems has spread, providing a foundation for a non-invasive (frameless) radiosurgical treatment [2]. Cone-beam computed tomography (CBCT) technology available on the modern linear accelerators (linacs) allows generating high-resolution 3D image sets of the patient head at the time of stereotactic treatments [3–5].

One of the main challenges in SRS is ensuring accurate delivery of radiation to small targets. An important step within the quality assurance (QA) at the time of treatment is to verify the alignment of the target center with the radiation isocenter of the treatment unit. Lutz et al. [6] developed a technique ("Winston-Lutz test") using a target point simulator to verify the stereotactic coordinates prior to treatment. An end-to-end test [7] (E2E) may provide a comprehensive analysis of the overall performance of SRS system, from CT imaging to treatment plan delivery.

The aim of this work is to assess the spatial accuracy of CBCT-guided SRS treatments performed in our department. This was accomplished by designing an E2E test using radiochromic film (RCF) dosimetry. The analysis included the accuracy of image guidance at the time of the delivery as well as the accuracy of the radiation dose distribution calculated by the treatment planning system (TPS).

2. Methods and materials

2.1. Phantom

We used a home-made phantom consisting of two acrylic blocks measuring 15 cm × 15 cm × 5 cm (Fig. 1a). Four linear radio-opaque marks (copper) were engraved in the lower block marking a 5 × 5 cm^2 square. A cross-hair passing through its center

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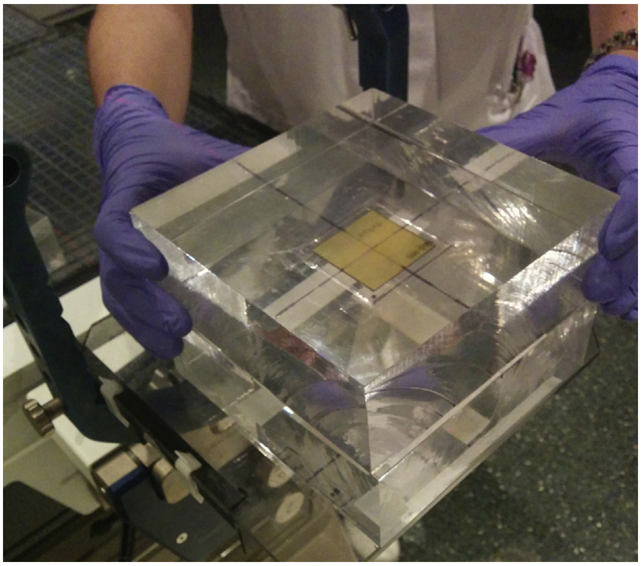

Fig. 1a. Acrylic phantom used for film E2E test.

was outlined (phantom cross-hair). In addition, four lead markers were added to indicate this cross-hair. The phantom was scanned (Somaton Biograph CT scanner, Siemens, Germany) with 1.25 mm slice thickness, 150 mm field of view (FOV), and 512 × 512 pixel matrix, which resulted in a voxel size of 0.3 × 0.3 × 1.25 mm^3. The phantom was scanned with no film inside. The CT images were transferred to the Eclipse TPS (version 10.0, Varian Medical Systems, Palo Alto, CA). The 5 × 5 cm^2 radio-opaque square was localized and its center was set as the origin of the CT image volume (Fig. 1b). The isocenter of each SRS plan computed on the phantom was placed at the center of the 5 × 5 cm^2 radio-opaque square. So, when a coronal dose plane containing the 5 × 5 cm^2 square was exported from the Eclipse TPS, the center of the dose matrix matched with the planned isocenter.

2.2. Film dosimetry

Radiochromic film was considered the dosimeter of choice in our work due to its high-spatial resolution and weak energy dependence [8,9]. Gafchromic EBT3 films (8x10F model, Ashland Specialty Ingredients, Advanced Materials Group, Wayne, NJ) in conjunction with a flatbed colour scanner (Epson V750 Pro, Epson Seiko Corporation, Nagano, Japan) were used. Several publications have shown the suitability of EBT3 films for stereotactic radiosurgery quality assurance [10,11].

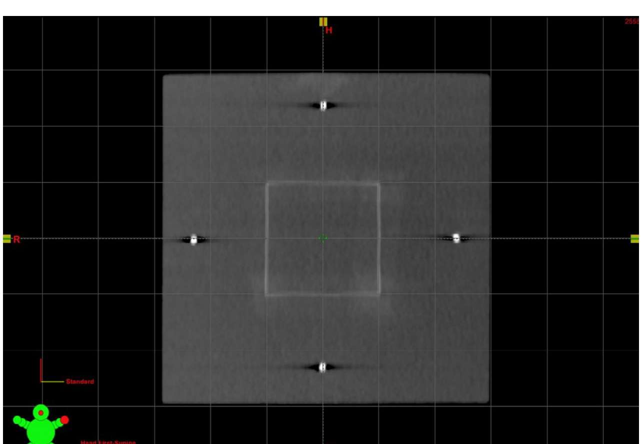

Fig. 1b. Phantom coronal plane of the planning CT scan, showing the 5 × 5 cm^2 radio-opaque square used for image registration with the CBCT scan.

Film dosimetry was performed using the triple channel method implemented in the FilmQA Pro software (version 2015; Ashland Specialty Ingredients, Advanced Materials Group, Wayne, NJ). This method is an approach to process radiochromic film data that uses all three colour channels of a scanned image to estimate and correct for uniformity deviations from the calibrated average film-scanner response [12].

Pieces of 4 × 4 cm^2 were cut from an entire EBT3 film using scissors. We tracked all the pieces of film by using permanent marker indentations for labelling and to indicate the piece orientation (portrait) with respect to the initial sheet length/width orientation. Also, four marks ("fiducials") showing the 4 × 4 cm^2 square center were outlined on each piece of film with a permanent ink pen.

To assess the dose-response curve for the EBT3 film, six 4 × 4 cm^2 patches (calibration films) were irradiated in a separate way to doses of 0, 2, 4, 8, 16 and 30 Gy, with a 20 × 20 cm^2 field size of a 6 MV photon beam from a Varian Clinac 2100 CD linac (Varian Medical Systems). This large field size (20 × 20 cm^2) was used to ensure that a homogenous dose was delivered to each calibration film patch (4 × 4 cm^2). The film EBT3 shows a negligible energy dependence over a range of clinically used photon energies [8,9]. As the change in field size represents a change in the energy spectrum, it can be assumed that the film EBT3 response is not affected significantly by varying the size of the radiation field. Therefore, we think that EBT3 films have no energy dependence significantly to the irradiation conditions used in our work.

All exposed films were digitized using the Epson V750 Pro scanner after twenty hours of irradiation. The scanner was warmed up for 30 min before use. Scanning was performed in transmission mode at 48 bit RGB (16 bits per colour channel) and with a spatial resolution of 72 dpi (0.35 mm/pixel). The obtained images were saved in TIFF file format. Each piece of film was positioned in the center of the scanner plate. To eliminate film curling, a large plate of transparent glass was used to completely cover the films during scanning. Prior to the scanning session, five successive blank scans were taken for scanner warm-up. All pieces of film were scanned five times and considered only the last reading for dosimetric analysis.

2.3. Dose calculation and treatment planning: Design of the E2E test

Five single-dose SRS patients treated in our department were randomly included in this work (target diameter ranged from 10 to 26 mm). The SRS patient plans were calculated in the Eclipse TPS for delivery using a Varian Clinac 2100 CD linac equipped with the Millennium 120 MLC (5 mm width at isocenter distance on central leaves) and the kilovoltage On-Board Imaging (OBI) system. Plans were designed using non-coplanar multiple fields of 6 MV photons. Dynamic intensity modulated radiotherapy (IMRT) technique was used in all plans with a dose rate of 600 MU/min. The beam's eye view field apertures ranged from 0.9 to 6.6 cm^2. The Analytical Anisotropic Algorithm (AAA, version 10.0) was used for dose calculation with 1.0 mm grid size. The accuracy of the AAA model for small fields was analyzed previously in our department [13].

Each SRS plan was mapped to our acrylic phantom by placing the isocenter at the center of the 5 × 5 cm^2 radio-opaque square. The resulting phantom-based plan (from now on referred to as "E2E plan") was recalculated by keeping the monitor units of its original clinical SRS delivery, as well as the dose algorithm and calculation grid. A CBCT field setup was included in the E2E plan and it was exported to Aria (version 10, Varian Medical Systems) record and verify system to be delivered. Also, a 20 × 20 cm^2 dose matrix