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Evaluation of the setup margins for cone beam computed tomography–guided cranial radiosurgery: A phantom study

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ABSTRACT

The aim of this study is to evaluate the setup margins from the clinical target volume (CTV) to planning target volume (PTV) for cranial stereotactic radiosurgery (SRS) treatments guided by cone beam computed tomography (CBCT). We designed an end-to-end (E2E) test using a skull phantom with an embedded 6mm tungsten ball (target). A noncoplanar plan was computed (E2E plan) to irradiate the target. The CBCT-guided positioning of the skull phantom on the linac was performed. Megavoltage portal images were acquired after 15 independent deliveries of the E2E plan. The displacement 2-dimensional (2D) vector between the centers of the square field and the ball target on each portal image was used to quantify the isocenter accuracy. Geometrical margins on each patient's direction (left-right or LR, anterior-posterior or AP, superior-inferior or SI) were calculated. Dosimetric validation of the margins was performed in 5 real SRS cases: 3-dimesional (3D) isocenter deviations were mimicked, and changes in CTV dose coverage and organs-at-risk (OARs) dosage were analyzed. The CTV-PTV margins of 1.1 mm in LR direction, and 0.7 mm in AP and SI directions were derived from the E2E tests. The dosimetric analysis revealed that a 1-mm uniform margin was sufficient to ensure the CTV dose coverage, without compromising the OAR dose tolerances. The effect of isocenter uncertainty has been estimated to be 1 mm in our CBCT-guided SRS approach.

Introduction

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 systems has spread, providing a foundation for a noninvasive (frameless) radiosurgical treatment.[2] Cone beam computed tomography (CBCT) technology available on the newer linear accelerators (linacs) allows generating high-resolution 3-dimensional (3D) image sets of the head at the time of SRS treatment. Chang *et al.*[3] concluded that CBCT imaging can be used to guide SRS treatment setup with accuracy comparable to the conventional frame-based stereotactic systems reported in the literature.[4]

One of the main challenges in SRS is ensuring accurate delivery of radiation to small targets. An important step within the quality assurance (QA) of SRS is to verify the alignment of the target center with the radiation center of the treatment unit. Lutz *et al.*[5] developed a technique ("Winston-Lutz test") using a target point simulator to verify the stereotactic coordinates before treatment. In the case of image-guided SRS, a crucial part of the QA process is to ensure the coincidence of the imaging isocenter with the radiation treatment isocenter, as they are associated with different mechanical systems. The procedure described by Yoo *et al.*[6] to test this coincidence involves aligning a phantom with external lasers, imaging the phantom, and noting any discrepancy between the imaging isocenter and the center of the phantom. However, this kind of test is used for checking the alignment of the imaging isocenter with a surrogate for the radiation isocenter, instead of the actual radiation treatment isocenter. Kry *et al.*[7] proposed an end-to-end (E2E) test that mimics the clinical image-guided radiotherapy workflow to verify the final target alignment (based on imaging) with the radiation treatment isocenter.

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In SRS, the lesion (gross tumor volume [GTV]) is normally defined using fine-cut contrast-enhancing (T1) magnetic resonance (MR) imaging. The clinical tumor volume (CTV) takes into account the microscopic extension of the tumor beyond the GTV. The margin GTV-CTV is normally in the range of 0 to 1 mm for brain metastases.[8] Owing to several uncertainty sources (as setup error), the CTV should be expanded to yield a planning target volume (PTV) to ensure the clinical target dosage.[9] The CTV to PTV expansion depends on a variety of factors, including the precision and accuracy of MR imaging; the registration of computed tomography (CT) or MR image sets during planning; the accuracy of the image guidance system; intrasession patient's positioning; and the accuracy and precision of the radiation treatment machine.

The aim of this work is to calculate the necessary setup margins from CTV to PTV to account the accuracy of the isocenter for CBCT-guided single-dose SRS treatments. This study is limited to only margins to account for variations of the radiation isocenter (including couch rotations) and because of CBCT guidance at the time of treatment. To this purpose, an E2E test using a skull phantom with a metal ball embedded was designed, and a formalism for CTV-PTV margin calculation was proposed. The margins obtained were dosimetrically validated for 5 patients previously treated in our department.

Methods and Materials

Design of the E2E test

We designed an E2E QA test that mimics our workflow of CBCT-guided SRS treatments, from planning CT acquisition to final treatment delivery. An anthropomorphic phantom containing a human skull was used. A 6-mm diameter tungsten ball (simulating a small target) was embedded into the phantom. The phantom was placed in a stereotactic head-invasive frame (Fig. 1), as a method to ensure the immobilization of the phantom during the tests.

The skull phantom was CT scanned (head first supine) with 1-mm slice thickness, field of view of 350 mm, and a 512 × 512 reconstruction matrix, in a Somaton Sensation CT (Siemens, Germany). A CT stereotactic localization box (BrainLAB AG, Germany) was used during CT imaging. The CT images were transferred to iPlan v. 4.1 (BrainLAB AG, Germany) for stereotactic localization. This ball plays the role of the CTV in the phantom case. Finally, the images were sent to the Eclipse v. 10 treatment planning system (Varian Medical Systems, Palo Alto, CA), and the tungsten ball was outlined. The Eclipse system was configured for 6-MV radiation beams of a Varian Clinac 2100 CD, equipped with the Millennium 120 multileaf collimator (MLC) and a standard 4-dimensional couch (Varian Exact Couch). The imaging systems of the linac were a megavoltage (MV) aSi-500 electronic portal image device (EPID) and a kilovoltage n-board imaging (OBI).

An E2E plan with the isocenter located at the center of the contoured tungsten ball was designed. The E2E plan consisted of 10 noncoplanar 20 × 20 mm^2 fields shaped using the Millennium 120 MLC. The following combinations of gantry and couch rotations were used: G220T270, G220T315, G270T0, G270T315, G0T0, G90T0, G90T45, G140T45, G140T90, and G180T0, where G means gantry angle and T means couch angle (given in degrees according to the Varian IEC 601-2-1 scale). Collimator rotation was not included because all SRS treatments are planned in our clinical routine with collimator at zero position. A CBCT field setup was included in the E2E plan. Finally, the E2E plan was exported to the Aria v. 10 record and verify system (Varian Medical Systems, Palo Alto, CA).

The planned isocenter position relative to the CT stereotactic localization box was also established in the iPlan treatment planning system. In all, 4 target positioner sheets depicting the planned isocenter were printed out of iPlan. These were attached to a target positioner box (BrainLAB AG, Germany) for phantom setup.

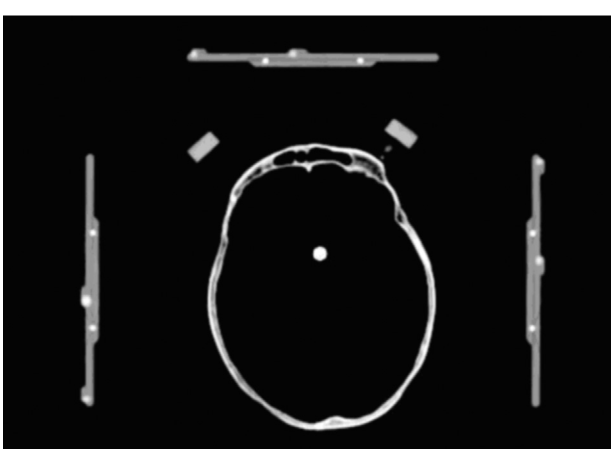

Fig. 1. Planning CT scan of the skull phantom with the 6-mm diameter tungsten ball used as target.

Performing the E2E test

The skull phantom was positioned at the linac couch using a dedicated couch adapter (BrainLAB couch mount), where the head frame was attached. The assembly consisted of the linac couch and the BrainLAB couch mount and can move remotely in 4 degrees of freedom. The 3 translational movements are along the lateral or left-right (LR) direction, vertical or anterior-posterior (AP) direction, and longitudinal or superior-inferior (SI) direction. The rotational movement is the couch rotation about the vertical axis, *i.e.*, along the coronal plane.

The skull phantom with the target positioner box was set up using the room lasers at the reference couch angle 0°. Then, the positioning frame was removed from the phantom and random misalignments within 5 mm were manually applied for each direction (RL, AP, and SI) using 3 couch translations. Rotational setup errors were not forced to the skull phantom, as the linac couch is not able to correct them. These errors are addressed in the clinical practice using an online procedure developed in our department,[10] where only translational corrections are required.

The CBCT scan programmed in the E2E plan was acquired. The "pelvis" scanning protocol consisted of 655 projections acquired during 360-degree gantry rotation with an x-ray technique of 125 kVp, 80 mA, and 13 ms for each projection. The CBCT image acquisition was performed with a half-fan bow-tie filter added. We have chosen the "pelvis" protocol (half-fan technique) over the "high-quality head" mode of the OBI system because the "pelvis" mode usually produces images with better quality. Axial slices were reconstructed using a field of view of 260 mm, 384 × 384 matrix, and 1.0 mm slice thickness. The CBCT scan was registered to the planning CT using OBI v.1.5 software (Varian Medical Systems, Palo Alto, CA). The required shifts to correct the skull phantom position were remotely applied. No image was acquired to verify the shifted position. Subsequently, MV portal images were acquired for each treatment field of the E2E plan. No image-guided corrections were performed after each couch rotation. To optimize the geometrical resolution, the EPID was positioned at a distance of 180 cm from linac source, giving a pixel size of 0.4 mm at the isocenter level.

The E2E test designed in this work includes several inaccuracies sources: CBCT isocenter accuracy, radiation isocenter variation, accuracy of CBCT guidance and couch motions at the time of treatment, accuracy to delineate the ball in the Eclipse, and MLC positioning. The E2E plan was delivered 15 times during the year 2014, within the QA program for SRS established in our department.

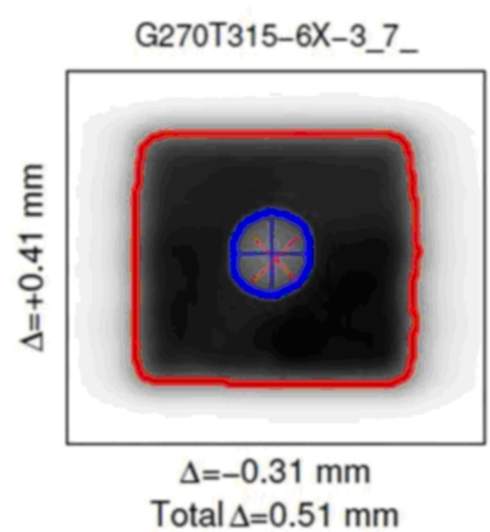

Fig. 2. Example of analysis of a MV image. Red cross mark: radiation field center. Blue cross mark: ball center. The distance between the 2 centers (Total Δ) as well as its horizontal and vertical (Δ) components are calculated. (Color version of figure is available online.)