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Physics Contribution

Spine Stereotactic Body Radiotherapy Utilizing Cone-Beam CT Image-Guidance With a Robotic Couch: Intrafraction Motion Analysis Accounting for all Six Degrees of Freedom

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Summary

Stereotactic body radiotherapy (SBRT) for spine tumors requires precise delivery in order to deposit high doses of radiation to the target while sparing the adjacent spinal cord. This paper describes a delivery technique with: near-rigid body immobilization; intrafraction cone-beam CT; corrections in all six degrees-of-freedom with a robotic couch; and strict repositioning thresholds. Minimal

Purpose: To evaluate the residual setup error and intrafraction motion following kilovoltage cone-beam CT (CBCT) image guidance, for immobilized spine stereotactic body radiotherapy (SBRT) patients, with positioning corrected for in all six degrees of freedom.

Methods and Materials: Analysis is based on 42 consecutive patients (48 thoracic and/or lumbar metastases) treated with a total of 106 fractions and 307 image registrations. Following initial setup, a CBCT was acquired for patient alignment and a pretreatment CBCT taken to verify shifts and determine the residual setup error, followed by a midtreatment and posttreatment CBCT image. For 13 single-fraction SBRT patients, two midtreatment CBCT images were obtained. Initially, a 1.5-mm and 1° tolerance was used to reposition the patient following couch shifts which was subsequently reduced to 1 mm and 1° degree after the first 10 patients.

Results: Small positioning errors after the initial CBCT setup were observed, with 90% occurring within 1 mm and 97% within 1°. In analyzing the impact of the time interval for verification imaging (10 ± 3 min) and subsequent image acquisitions (17 ± 4 min), the residual setup error was not significantly different ($p > 0.05$). A significant difference ($p = 0.04$) in the average three-dimensional intrafraction positional deviations favoring a more strict tolerance in translation (1 mm vs. 1.5 mm) was observed. The absolute intrafraction motion averaged over all patients and all directions along x, y, and z axis (± SD) were 0.7 ± 0.5 mm and 0.5 ± 0.4 mm for the 1.5 mm and 1 mm tolerance, respectively. Based on a 1-mm and 1° correction threshold, the target was localized to within 1.2 mm and 0.9° with 95% confidence.

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intra-fraction motion was achieved.

Conclusion: Near-rigid body immobilization, intrafraction CBCT imaging approximately every 15−20 min, and strict repositioning thresholds in six degrees of freedom yields minimal intrafraction motion allowing for safe spine SBRT delivery.

Keywords: Stereotactic body radiotherapy, Cone-beam CT, Image-guided radiotherapy, Intrafraction motion, Spine radiosurgery

Introduction

Stereotactic body radiotherapy (SBRT) for spine tumors refers to high-dose per fraction radiation (>5 Gy per fraction) delivered conformally to a spinal segment, precisely with the use of image guidance, in few fractions (1, 2). There are several technical challenges in treating spine tumors with SBRT, which predominantly stem from the precision that is required because of the proximity of the target to the adjacent spinal cord, and the aim of keeping the dose to the spinal cord just at tolerance. If the spinal cord dose is too high, then the patient is at risk of radiation myelopathy (3, 4); if it is too low, then underdosing epidural disease increases the risk of failure (5). It has been shown that even small motions of 1−2 mm in translational axes, and in conjunction with fine rotational motions, can significantly affect the spinal cord dose delivered (6−8). This sensitivity of the spinal cord to fine positional deviations is the result of the steep dose gradient positioned adjacent to the spinal cord, which is often within a millimeter or less beyond the target volume (5) (Fig. 1).

Unlike frame-based brain radiosurgery (9), extracranial radiosurgery requires dose distributions of extreme complexity because of the irregular shape of a vertebral segment and the spinal cord that is to be spared is essentially lying within the planning target volume (PTV). Furthermore, immobilization of body targets is challenging because an invasive frame providing rigid immobilization is impractical (10), and factors such as organ (11) and patient motion (12, 13) may influence delivery in all six degrees of freedom (6-DOF). Therefore, within the limits of current radiation therapy technology, it is essential to ensure as precisely as possible that the intended dose is delivered.

Image-guided radiotherapy (IGRT) is fundamental to the practice of spine SBRT (2). For example, intrafraction imaging approximately every 5 min using stereoscopic X-ray coupled with near real-time linac positioning corrections in 6-DOF (Cyberknife technology, Accuray, Sunnyvale, CA), has been reported to maintain the position of a spinal target to within 1 mm and 1° (13). However, multileaf collimator−based linac technologies are distinct from the Cyberknife such that the linac position cannot compensate for patient motion, and robotic couch technology is required to perform the 6-DOF positioning corrections. Most multileaf collimator−based systems for SBRT are also equipped with a gantry mounted CBCT device for image-guidance, with the advantage of obtaining three-dimensional volumetric CT data compared with planar X-ray image matching on bone. However, CBCT imaging requires that treatment be stopped, the image acquired and processed, and subsequent positioning corrections performed (if needed) before treatment can resume. This prolongs the overall treatment time and limits the number of intrafraction CBCT images that can practically be performed during a fraction, and near-rigid body immobilization systems are thought to be important to limit patient motion in-between CBCT intrafraction imaging intervals. One commercially available device is the BodyFIX immobilization system (Medical Intelligence, Schwabmuenchen, Germany) and, for spine, it has been shown to be effective in minimizing intrafraction patient motion to permit margin reductions for the PTV and planning organ at risk volumes (PRV) (14, 15).

We developed our spine SBRT technique based on the BodyFIX near-rigid body immobilization system, image-guidance using a kilovoltage cone-beam CT (CBCT) mounted on the Elekta Synergy Beam Modulator linac system (Elekta, Crawly, United Kingdom), and precise couch motions in 6-DOF using the Hexapod (Medical Intelligence, Schwabmuenchen, Germany) robotic couch (16). Our image-guidance protocol consisted of a CBCT to correct the initial patient setup errors followed by a verification CBCT to assess the residual setup error. Intrafraction and posttreatment CBCT images were then acquired to verify that the patient did not move beyond our set tolerance during treatment (16). For single-fraction spine SBRT, we added a second intrafraction CBCT as treatment times are longer than those fractionated (2−5 fractions) SBRT courses. This report describes our residual setup errors and subsequent intrafraction motion specific to our published SBRT technique (16).

Methods and Materials

We analyzed data from 42 consecutive patients treated for thoracic or lumbar spine metastases using SBRT from January 2009 through July 2010. All patients were immobilized in the Elekta BodyFIX system and treated on the Elekta Synergy unit equipped with a kilovoltage CBCT image-guidance system and the Hexapod robotic couch. The BodyFIX device consists of a dual vacuum pump, BlueBAG vacuum cushion, and a top cover sheet. We based the initial setup on isocenter tattoos, and/or marks on the BlueBAG. Subsequently, localization was then determined using CBCT for all patients. The CBCT images were registered to the planning CT using the automatic gray value alignment for maximization of mutual information. Following necessary manual adjustments, the Hexapod robotic couch corrected any positional misalignments in 6-DOF. Positioning was verified and residual setup error determined on the basis of a subsequent verification CBCT image before treatment. For fractionated treatments, a single midfraction CBCT was acquired after half the beams were delivered. For single-fraction treatments, two intrafraction CBCT scans were performed. The first intrafraction CBCT scan was taken after the first third of the beams were delivered, and the second after two thirds of the beams had been delivered. At treatment completion, a posttreatment CBCT image was acquired to capture final positioning motions. If the patient had been immobilized in the BodyFIX system for more than 60 min, the last CBCT was not obtained to adhere to the manufacturer's guidelines, because there may be an increased risk of pressure-related injury.