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Setup uncertainties in linear accelerator based stereotactic radiosurgery and a derivation of the corresponding setup margin for treatment planning

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ABSTRACT

Purpose: In the present study, clinical stereotactic radiosurgery (SRS) setup uncertainties from image-guidance data are analyzed, and the corresponding setup margin is estimated for treatment planning purposes.
Methods: Patients undergoing single-fraction SRS at our institution were localized using invasive head ring or non-invasive thermoplastic masks. Setup discrepancies were obtained from an in-room x-ray patient position monitoring system. Post treatment re-planning using the measured setup errors was performed in order to estimate the individual target margins sufficient to compensate for the actual setup errors. The formula of setup margin for a general SRS patient population was derived by proposing a correlation between the three-dimensional setup error and the required minimal margin.
Results: Setup errors of 104 brain lesions were analyzed, in which 81 lesions were treated using an invasive head ring, and 23 were treated using non-invasive masks. In the mask cases with image guidance, the translational setup uncertainties achieved the same level as those in the head ring cases. Re-planning results showed that the margins for individual patients could be smaller than the clinical three-dimensional setup errors. The derivation of setup margin adequate to address the patient setup errors was demonstrated by using the arbitrary planning goal of treating 95% of the lesions with sufficient doses.
Conclusions: With image guidance, the patient setup accuracy of mask cases can be comparable to that of invasive head rings. The SRS setup margin can be derived for a patient population with the proposed margin formula to compensate for the institution-specific setup errors.

Introduction

Linear accelerator (linac) based stereotactic radiosurgery (SRS) has been widely used in the treatment of brain metastases and other types of brain lesions [1–5]. In single-fraction radiosurgery, geometric accuracy is always a major concern. There have been several investigations on the sources and magnitudes of geometric uncertainties in SRS [6–13], as well as phantoms for dose distribution verification [14]. During SRS procedures, patients are immobilized and positioned using frame-based or frameless fixation devices. Traditionally, invasive head frames have been considered robust and accurate means of patient setup and fixation, although frameless devices can reach comparable accuracies with appropriate image guidance [12,13,15].

In linac based SRS, radiation dose can be delivered using various techniques with non-coplanar beam configurations, depending on the capacities of the linac and accessories. These techniques include static conformal beams, intensity-modulated radiation therapy (IMRT), circular cones, static conformal arcs, and dynamic conformal arcs [16–21]. Recently, volumetric modulated arc therapy has also been validated for SRS treatment [21,22]. The numerous combinations of fixation devices, image guidance, and delivery techniques for SRS might result in different patterns of geometric uncertainties.

In the present study, we investigate the setup uncertainties in the SRS patients treated at our department. These patients were immobilized using either frame-based invasive head ring or non-invasive thermoplastic mask. The majority of the patients were treated using dynamic conformal arc technique, and the remainder was treated using circular cones or IMRT. In the present study, we retrospectively review the patient setup data from an image guidance system and their treatment plans. The purpose of this study is to summarize the geometric uncertainties of the immobilization devices, and to derive appropriate setup margin formulas to address these geometric uncertainties for SRS cases.

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Although the patient-specific setup errors in SRS treatment might be measured on individual bases, it is impossible to predict them for each patient during the planning stage. For a patient population, it is more relevant to describe the setup uncertainties using the standard deviation of setup errors. Throughout this manuscript, the terms “setup error” and “setup uncertainties” refer to individual patients and a patient population, respectively, as suggested by the above introduction. In order to ensure the tumor dose coverage, an expansion margin is applied to the target in treatment planning. One component of the target expansion margin is the “setup margin” as defined in the International Commission of Radiation Units and Measurements (ICRU) Report 62 [23]. Intuitively, one would determine the setup margin using the expected setup uncertainties. This approach certainly requires the knowledge of setup error distribution for a patient population, of which van Herk’s work [24] is representative.

In the present study, we attempt to focus on the random setup uncertainties. To compensate for these uncertainties, it is hypothesized in this work that the necessary setup margin is correlated with setup uncertainties, as well as the target expansion margin chosen for the patient population during treatment planning. Briefly, our approach takes the following steps in order to determine the setup margin for a patient population. Firstly, the minimal margin needed for each individual patient is estimated from the patient-specific setup errors measured using an image guidance system. Secondly, setup margin is derived for the above patient population in order to address the setup uncertainties, so that for a given percentage of the patients, the targets would receive adequate radiation dose. To implement our approach, we also recommend the criterion of image guided re-localization, so that the setup margin may be further reduced.

Methods

Patients

The subjects of this Institutional Review Board-approved study were adult patients treated with SRS at our department between January 2009 and January 2013. The inclusion criteria consisted of the following: patients were immobilized with invasive head ring or thermoplastic mask; patients underwent single-fraction brain SRS treatment; and at least one set of image guidance data was available for the treated brain lesion. A total of 110 patients were enrolled, of whom 105 lesions were treated with head ring, and 57 lesions were treated with mask as the fixation device.

Treatment planning

Patients were immobilized using the BrainLab head frame with brain localizer (BrainLab AG, Feldkirchen, Germany). At our institution, clinical patient selection for SRS procedures, the fixation device, and the dose prescription are dictated by the attending radiation oncologists, and/or jointly by neurosurgeons. Patients immobilized using invasive head rings were scanned on the same day of treatment. Patients immobilized using non-invasive thermoplastic masks were usually scanned prior to the day of treatment. Treatment planning images were acquired on a computed-tomography (CT) simulator at 1.2 mm slice thickness in axial mode.

After the gross tumor volume (GTV) or clinical tumor volume (CTV) was contoured, uniform geometric margins of 0–2 mm were added to form the planning tumor volume (PTV), as dictated by the attending radiation oncologists and/or neurosurgeons. These patients were treated on a Novalis® radiosurgery system (BrainLab AG) using 6 MV photon beams. When the patients were treated with dynamic conformal arcs, the treatment doses were most commonly prescribed to the 90% isodose level. In these plans, the multileaf collimator (MLC) was used to make the prescribed isodose lines conform to the PTV as closely as possible, while maintaining PTV coverage. In general, 90% of the prescribed dose was to completely encompass the PTV; the prescribed dose would cover at least 95% of the defined target volume, if achievable. Dose constraints to critical structures were determined based on published guidelines and clinical trials.

Image guidance

The Novalis linac was equipped with the ExacTrac® patient position monitoring system (BrainLab AG). It has been verified that the ExacTrac system used in this study is able to reach sub-millimeter accuracy in target localization [25]. ExacTrac would report the three translational and three rotational setup errors in its coordinate system, in which the lateral, longitudinal, and vertical coordinates are equivalent to x, y, and z in the IEC61217 patient coordinate system. These translational directions define the corresponding rotation axes. In this sense, the numerical “setup errors” defined in this study are those indicated by the ExacTrac system. Patients in masks were repositioned by shifting the couch until the ExacTrac system reported less than 1 mm translational error in each direction.

Setup margin for dynamic arc

In the present study, only the additional geometric target margin associated with setup errors is investigated. The term “margin” in this text does not take into account other uncertainties in SRS, such as the residual setup error by shifting based on the imaging system, which was studied in a separate work [26]. Part of the patients treated with dynamic conformal arc, either in head ring or mask, had ExacTrac data immediately before the treatment. The dosimetric parameters of treatment plans were compared between the head ring and mask cases, including the conformity index, the homogeneity index (D_5/D_{95}), and the average distance between the prescribed isodose lines to the PTV. No statistically significant differences were observed between the two patient groups. Therefore, these patients were analyzed as a single group to study the setup margin for dynamic conformal arc delivery, provided the lesions located within the brain tissue were not highly irregular.

For each lesion, a retrospective plan was then generated from the original treatment plan by applying the ExacTrac-detected translational setup errors to the beam isocenter, while the arc angles and MLC shapes were frozen, and the monitor units remained the same. In the retrospective plans, translational setup errors detected by ExacTrac were applied because this approach was believed to better reflect clinical reality. The rotational errors were neglected because other investigators indicated that moderate rotational errors would not result in significant dosimetric consequences in SRS cases [27,28]. In the original plan, uniform margins were added to the target volume to determine a setup margin such that with this margin, the expanded target had the same minimum dose as the shifted target in the retrospective plan. This retrospective plan would show how the target volume dose distribution degraded when setup errors occurred. The reason of choosing the minimum dose as the criterion was to ensure a sufficient margin. This criterion is analogous to that used by van Herk et al.: “for 90% of the patient population, the minimum dose to the CTV must be 95% of the nominal dose or higher [24].” A uniform setup margin was applied because the uncertainties of the translational setup errors had approximately the same magnitude, as shown in the next section.

Based on the above study, margin formulas were developed for dynamic conformal arc SRS treatments. Inspired by the method of Papiez et al. [29], we propose using a two-dimensional Gaussian function of the following form to estimate the setup margin for the patients in our series:

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