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PHYSICS CONTRIBUTION

COMPARISON OF PLANNED DOSE DISTRIBUTIONS CALCULATED BY MONTE CARLO AND RAY-TRACE ALGORITHMS FOR THE TREATMENT OF LUNG TUMORS WITH CYBERKNIFE: A PRELIMINARY STUDY IN 33 PATIENTS

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Purpose: To compare dose distributions calculated using the Monte Carlo algorithm (MC) and Ray-Trace algorithm (effective path length method, EPL) for CyberKnife treatments of lung tumors.

Materials and Methods: An acceptable treatment plan is created using Multiplan 2.1 and MC dose calculation. Dose is prescribed to the isodose line encompassing 95% of the planning target volume (PTV) and this is the plan clinically delivered. For comparison, the Ray-Trace algorithm with heterogeneity correction (EPL) is used to recalculate the dose distribution for this plan using the same beams, beam directions, and monitor units (MUs).

Results: The maximum doses calculated by the EPL to target PTV are uniformly larger than the MC plans by up to a factor of 1.63. Up to a factor of four larger maximum dose differences are observed for the critical structures in the chest. More beams traversing larger distances through low density lung are associated with larger differences, consistent with the fact that the EPL overestimates doses in low-density structures and this effect is more pronounced as collimator size decreases.

Conclusions: We establish that changing the treatment plan calculation algorithm from EPL to MC can produce large differences in target and critical organs' dose coverage. The observed discrepancies are larger for plans using smaller collimator sizes and have strong dependency on the anatomical relationship of target-critical structures. © 2010 Elsevier Inc.

SBRT lung, Monte Carlo calculation, CyberKnife.

INTRODUCTION

The successful application of the principles of intracranial stereotactic radiosurgery (SRS) to extracranial sites including the lung was first reported in 1995 by Blomgren *et al.* (1). Applying these principles to hypofractionated stereotactic body radiation therapy (SBRT) requires both precise dose targeting and precise dose shaping, thereby allowing high doses to be delivered to the target in a single or a small number of fractions, sparing at the same time surrounding critical structures (1, 2). The early reports on studies in SBRT on limited-stage non–small-cell lung cancer (1–13) all show high rates of tumor response, local control probability of 71–100%, and overall survival rates of 32–79% with only limited toxicity. Based on the reported success of others using linac-based, stereotactic, high-dose hypofractionated radiotherapy, treating patients with non–small-cell lung cancer with the CyberKnife was proposed. Descriptions of CyberKnife treatment planning for pulmonary malignancies have been published (14–16). The first report of CyberKnife therapy for isolated lung tumors was by Whyte *et al.* (14).

In most of these studies, however, no detailed information about the calculation model is given, even though for targets in the lung, the computed dose distributions strongly depend on the calculation model and whether heterogeneity corrections are performed. These differences may be even more significant for the small radiation fields used in SRS. When the planning target volume (PTV) is adjacent to or within a low-density region, treatment plans that use an attenuation corrected pencil beam or effective pathlength algorithm tend to overestimate the dose in the PTV and underestimate the broadening of the beam penumbra (17). Comparisons between various dose calculation methods for linac-based SBRT are reported (18–20). It is recognized that Monte Carlo–based techniques (21) are the most accurate methods of dose calculation available because they model the actual physical processes that lead to dose deposition including secondary electron distributions. In the early years of the

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CyberKnife Robotic Radiosurgery System, the dose calculation was based entirely on a ray-tracing algorithm with a simple pathlength density correction for heterogeneities, referred to below as effective path length method (EPL). However, the dose calculation based on a ray-tracing technique on the central beam axis may result in large discrepancies between calculated and delivered dose in heterogeneous body areas such as lung (22).

Recognizing that a more accurate algorithm would improve accuracy of dose calculation, particularly in lung, Accuray Inc., with external academic collaborators, developed a Monte Carlo algorithm for the CyberKnife Robotic Radiosurgery System (MC). The commissioning and implementation of this system is described (23, 24) and it became available for clinical treatments in late 2007. We have validated this MC algorithm in heterogeneous phantoms in a single-beam geometry (22). The results showed agreement between the MC calculated dose distributions and measured dose to within a few percent for the entire range of collimator sizes. The significance of the MC algorithm is to provide more accurate dose calculation in regions of tissue density heterogeneity. Because the lung is the largest nonunit density tissue, the largest differences in the dose calculation by the two different algorithms are expected. The MC algorithm is now being used at our institution for all CyberKnife treatments of pulmonary targets. The Ray-Trace algorithm, however, remains available and the user can choose to use either the EPL or MC algorithm for CyberKnife treatment planning. We discuss here the use of the MC algorithm and present a comparison of dose distributions calculated by MC and EPL for 33 patients treated. Furthermore, since the widely used pencil-beam algorithms for linac-based SBRT are based on the same effective pathlength method which forms the basis of the Ray-Trace (EPL) calculation method, the conclusions of our study are relevant to all SBRT of pulmonary targets regardless of radiation delivery system. And, we have found, in agreement with others (20), that calculations based on EPL overestimate the dose at the reference isodose level and lead to underdosage of the PTV. Therefore, the use of the MC or an algorithm derived from the MC application is recommended.

METHODS AND MATERIALS

CyberKnife treatment

The CyberKnife (Accuray Incorporated, Sunnyvale, CA) is a frameless stereotactic radiosurgery system consisting of a linear accelerator mounted on a robotic arm and is specifically designed for image-guided cranial and body radiosurgery delivered in a small number of fractions using multiple (typically 40–200) highly focused noncoplanar 6-MV beams. The system allows respiratory tracking by using a camera array in the treatment room that continuously images externally applied light-emitting diodes on the patient. The location of the light-emitting diodes is correlated with the location of the internal fiducials; the correlation model allows for continuous dynamic respiratory tracking and treatment throughout the respiratory cycle.

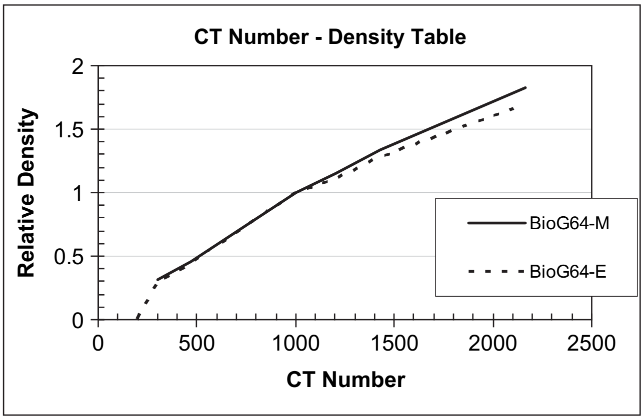

Fig. 1. The relationship between computed tomography number and relative mass (M) and electron density (E) is shown for the Siemens Biograph64 scanner used in our study.

Treatment planning and dose prescription

The treatment planning computed tomography (CT) consisted of continuous axial slices (1.5-mm thick) obtained while patients held their breath during normal breathing. The gross tumor volume and critical structures such as spinal cord, trachea, esophagus, bronchus, heart, and total lung were contoured. The planning target volume routinely included a 3–5 mm margin beyond the gross tumor volume to include microscopic extension and to accommodate targeting uncertainty. The dose was prescribed to the PTV, usually at the 60–80% isodose line. The inverse planning module was used to maximize dose conformality. Treatment followed shortly after and was delivered in three to five fractions over 3–8 days.

Each algorithm in the Multiplan treatment planning system requires the selection of a density table. It is recommended that the user enter the CT number vs. tissue density table, which applies to the CT scanner that will be used. The relationship of CT number and tissue density (mass density and relative electron density) for the CT scanner (denoted as Siemens Biograph64) used at our institution is shown in Fig. 1.

The treatment plan is first calculated using Multiplan, version 2.1, using EPL. This standard algorithm uses a ray-tracing function to calculate the dose contributed to a target voxel for each beam in the treatment plan. The tissue phantom ratio used in the dose calculation is determined for an effective depth obtained by summing the CT electron density relative to water contribution of each voxel along the ray from the source to the plane containing the target voxel. This effective depth is calculated on the central axis of each beam only and therefore corrects for density changes only for the primary component of the beam.

The MC dose calculation algorithm is an option on the Multiplan treatment planning system. It is based on MC methods that are well described in the literature; see American Association of Physicists in Medicine Report 85 (25) for a description of MC dose calculation in comparison to other calculation techniques in the context of tissue inhomogeneity corrections. MC as implemented for CyberKnife planning is described in detail by Deng *et al*. (23, 24) and takes advantage of the fact that the CyberKnife System has a single relatively low-energy X-ray beam (6 MV) and a fixed number of circular collimators.

We performed an EPL calculation using the CT number to density conversion applicable to the CT scanner on which the patient was scanned. After an acceptable distribution is obtained, the plan is recalculated, and, if necessary, optimized using MC. The final dose