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PHYSICS CONTRIBUTION

FOUR-DIMENSIONAL LUNG TREATMENT PLANNING IN LAYER-STACKING CARBON ION BEAM TREATMENT: COMPARISON OF LAYER-STACKING AND CONVENTIONAL UNGATED/GATED IRRADIATION

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Purpose: We compared four-dimensional (4D) layer-stacking and conventional carbon ion beam distribution in the treatment of lung cancer between ungated and gated respiratory strategies using 4DCT data sets.
Methods and Materials: Twenty lung patients underwent 4DCT imaging under free-breathing conditions. Using planning target volumes (PTVs) at respective respiratory phases, two types of compensating bolus were designed, a full single respiratory cycle for the ungated strategy and an approximately 30% duty cycle for the exhalation-gated strategy. Beams were delivered to the PTVs for the ungated and gated strategies, PTV(ungated) and PTV(gated), respectively, which were calculated by combining the respective PTV(Tn)s by layer-stacking and conventional irradiation. Carbon ion beam dose distribution was calculated as a function of respiratory phase by applying a compensating bolus to 4DCT. Accumulated dose distributions were calculated by applying deformable registration.
Results: With the ungated strategy, accumulated dose distributions were satisfactorily provided to the PTV, with D95 values for layer-stacking and conventional irradiation of 94.0% and 96.2%, respectively. V20 for the lung and Dmax for the spinal cord were lower with layer-stacking than with conventional irradiation, whereas Dmax for the skin (14.1 GyE) was significantly lower (21.9 GyE). In addition, dose conformation to the GTV/PTV with layer-stacking irradiation was better with the gated than with the ungated strategy.
Conclusions: Gated layer-stacking irradiation allows the delivery of a carbon ion beam to a moving target without significant degradation of dose conformity or the development of hot spots. © 2011 Elsevier Inc.

Carbon ion beam, CT, Four-dimensional, Layer-stacking, Lung, Treatment planning.

INTRODUCTION

Worldwide, more than 28 particle treatment centers were operating in 2008, including three carbon ion beam centers, and the construction of new centers is set to continue. Compared with photon beams, charged particle beams provide superior dose conformation and the minimization of excessive dosing to normal tissues. These strengths result from the characteristic increase in energy deposition of particle beams with penetration depth (proton and carbon ion beams) up to a sharp maximum at the end of the range (Bragg peak) (1). The National Institute of Radiological Sciences (NIRS) has treated more than 3,000 patients using carbon ion passive beams since 1994, and several clinical studies have been reported (2–5).

Although passive beam irradiation benefits from relatively simple treatment planning requirements, its disadvantage is the significant excessive dose delivered to normal tissues along the entrance of the target. Although beam scanning irradiation using proton beam and carbon ion beams was first introduced by Kanai *et al.* (6) and Goitein *et al.* (7), respectively, as long as 25 years ago, no treatment centers are yet using scanning irradiation to provide treatment to a moving target, and investigation continues at the research level (8, 9). Kanai *et al.* proposed layer-stacking irradiation, which uses passive proton beams to achieve higher dose conformation and thereby provide similar dose conformity to scanning irradiation (10). They were followed by Kanematsu *et al.*, who extended this idea to carbon ion beams and integrated it into the Heavy Ion Medical Accelerator in Chiba (HMAC) at the NIRS (11), and the NIRS has now been upgraded to provide layer-stacking irradiation. This advance represents a relatively easy means of upgrading treatment centers currently using passive beams.

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Several centers have reported treatment approaches to a moving target using passive beam irradiation (12–15). Because scanning irradiation irradiates respective beam spots as a function of time within the same layer and then changes to the next layer, repeating this process until the prescribed dose is delivered to the target, it should be naturally less robust against motion than passive irradiation (8, 9). In contrast, layer-stacking irradiation delivers a small spread-out of Bragg peak (SOBP) in a single layer at a time, and should therefore be more robust against motion than scanning irradiation, but more sensitive than conventional irradiation. These findings highlight the importance of evaluating respiratory-induced dose variation, including deformable registration, in layer-stacking irradiation.

Here, we evaluated 4D layer-stacking carbon ion beam distribution in lung cancer and compared findings between respiratory-ungated and respiratory-gated strategies.

METHODS AND MATERIALS

Layer-stacking irradiation method

The conventional particle beam irradiation method presently used at the NIRS is a passive irradiation technique, in which the treatment beam is laterally broadened by a pair of wobbler magnets and a scatterer, and the sharp Bragg peaks are broadened along the beam direction by a ridge filter (16). The SOBP length is fixed within the beam field (Fig. 1a).

To achieve higher dose conformation with passive beams similar to that with scanning irradiation, layer-stacking irradiation basically uses a fine ridge filter, a range shifter, and a multi-leaf collimator (MLC) (Figs. 1b–1d). Uniform dose distribution is achieved by combining a finite number of minipeaks (small SOBP) along a depth direction. The minipeak is shaped by a fine ridge filter (17) and shifted in 2.5-mm steps (layers) from the distal target position (first layer) to the proximal position (*n*th layer) by changing range filter thickness. The target is subdivided into regions with a 2.5-mm thickness in water along the depth direction. Beam field size is defined to fit the respective subdivided regions by changing the MLC opening width. To form a uniform SOBP using a broad-beam dose calculation algorithm, the MLC opening width should be fixed by selecting the largest opening width within a 30-mm depth in water from the most distal side.

Our lung treatment protocol uses a patient collimator (PTC) to shape the beam field, on the basis that beam fields shaped using an MLC are larger than those shaped using a PTC because of penumbra size. The advantage of layer-stacking irradiation is its higher dose conformation and lower dose to normal tissues, although when performed using an MLC only, the dose to normal tissues may be greater than that with conventional irradiation using a PTC, because the lateral penumbra using an MLC is approximately two times larger than that using a PTC. To solve this problem, we used both a PTC to shape the beam field to the target and an MLC to change the beam field to the respective layers. Other details, such as biophysical modeling and beam weight optimization, have been described elsewhere (11).

Treatment planning

4DCT imaging. The subjects of this study were 20 inpatients selected at random from among lung cancer patients receiving carbon beam radiotherapy. Patients gave informed consent before participation, and the study was approved by the Institutional Review Board of the NIRS. Relevant patient demographics, tumor pathology, size, and location are summarized in Table 1.

All 4DCT scans were performed with a 256 multi-slice CT scanner (256MSCT) under quiet free-breathing conditions, with respiration monitored by an NIRS-developed respiratory sensing system. Because the 256MSCT can acquire approximately 13 cm per single rotation, we did not move the table couch during 4DCT scanning (18, 19). Scan conditions were a 256 $\times$ 0.5-mm slice thickness and 0.5 s per rotation, but temporal resolution was substantially improved by adapting Feldkamp-Davis-Kress–based Parker weighting (20, 21). The breathing cycle was typically subdivided into 10 phases, with peak inhalation set as T00.

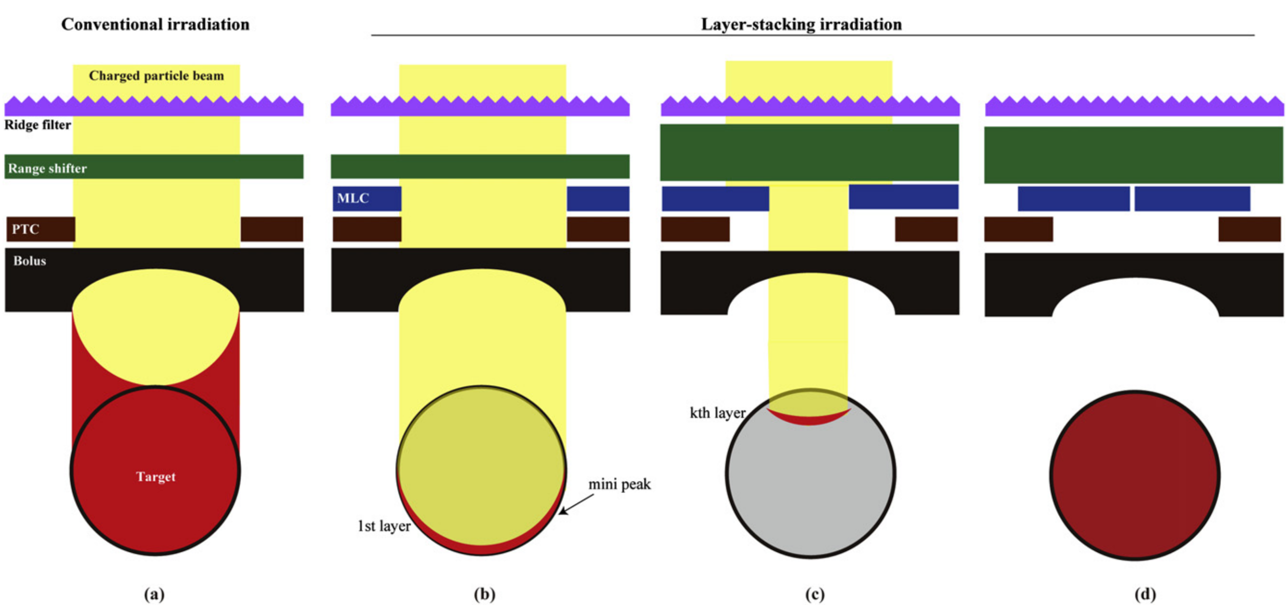

Fig. 1. Schematic drawing of the layer stacking irradiation method. (a) Conventional irradiation. (b) Irradiation first layer. (c) Irradiation *k*th layer. (d) Accumulated dose to the target.