

DOSIMETRIC IMPACT OF MULTIPLE ENERGY OPERATION IN CARBON-ION RADIOTHERAPY

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Abstract

In radiotherapy with a scanned carbon beam, its Bragg peak is shifted along beam direction either by inserting the range shifter plates (RS) or by changing the beam energy extracted from the synchrotron (ES). We propose a combined longitudinal scan technique where several beam energies are used in conjunction with the range shifter plates for slighter range shift in a single treatment (CS). In this study, this technique is evaluated from the viewpoint of dose distribution. Three target volumes of $60 \times 60 \times 60 \text{ mm}^3$ are located at 45, 85 and 125 mm in water, and uniform clinical dose is planned for these targets. Lateral dose falloffs at the center of SOBP are 6.6, 5.7 and 5.0 mm for these targets in CS, while they are 11.4, 8.5, 5.9 mm in RS and 5.7, 4.8, 4.6 mm in ES, respectively. The RBEs averaged over the targets are 2.72, 2.64 and 2.54 in CS, while they are 2.58, 2.55, 2.53 in RS and 2.73, 2.66, 2.60 in ES, respectively. These results revealed the usefulness of CS as a longitudinal scan technique with a good target conformity in carbon-ion radiotherapy.

INTRODUCTION

In 3D irradiation with pencil beam scanning, the narrow pencil beam is scanned across the target volume at various depths. The beam is scanned perpendicularly to the beam direction by a pair of deflection magnets, while its depth is shifted either by using energy degraders such as range shifters or by changing the beam energy extracted from the synchrotron. The former longitudinal scan technique (range shifter scanning: RS) is adopted in NIRS [1] while the latter technique (active energy scanning: ES) has been used in GSI [2] and HIT. In RS, the range shifter plates may broaden the spot size of the beam on a target and produce secondary fragments, which could adversely affect the depth-dose profile. Since the focused beam is desired in 3D irradiation with pencil beam scanning, it is preferable to change the beam energy directly from the synchrotron instead of using range shifter plates. In NIRS, we plan to shift to ES with an extended flattop operation providing beams with various energies in a single synchrotron cycle [3]. However, operation with ES requires a long term of accelerator tuning and commissioning tests for beam preparations. Additionally, in the synchrotron adopting a cycle-by-cycle energy variations, it takes several seconds to change the beam energy depending on the synchrotron operation cycle, leading to a long treatment time up to a few tenth of

minutes. We propose an alternative technique combining RS and ES, a combination scanning (CS), where eleven beam energies having the ranges from 4 to 30 cm with 2.5 cm intervals are prepared and used in conjunction with the range shifter plates for slighter range shift. In this study, CS is evaluated from the viewpoints of dose distributions.

IRRADIATION METHODS

Three longitudinal scan techniques designed at NIRS are briefly explained in this section.

Range Shifter Scanning (RS)

Fig. 1 shows the schematics of RS. In RS, the beam with a single energy is used throughout a treatment. The beam range is controlled by inserting the PMMA plates with desired thicknesses. This technique enables the desired range shift within a few hundred milliseconds. However, the range shifter plates may broaden the spot size of the beam on a target, and concurrently produce secondary fragments through nuclear reactions within them.

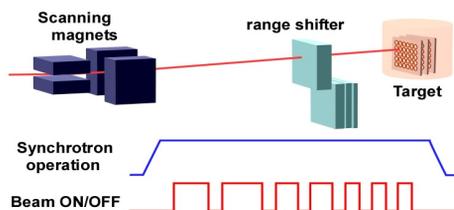


Figure 1: The schematics of RS operation.

Active Energy Scanning (ES)

Fig. 2 shows the schematics of ES. The beam energy is successively changed within a treatment by an energy step, corresponding to a water equivalent distance between two adjacent depth slices. With this technique, the beam range can be controlled without using energy degraders, and hence excellent depth-dose profile can be obtained. However, it takes a long time for commissioning processes to safely initiate this operation.

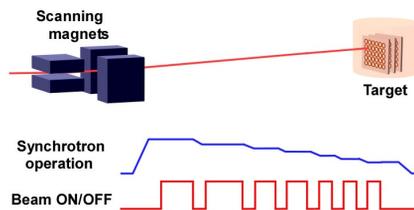


Figure 2: The schematics of ES operation.

Combination Scanning (CS)

Fig. 3 shows the schematics of CS. In CS, the beam range is roughly shifted by changing the beam energy from the synchrotron. Thin range shifter plates up to 3 cm are additionally used for slighter range shifts. In NIRS, we will prepare eleven beam energies having the ranges from 4 to 30cm with 2.5 cm intervals.

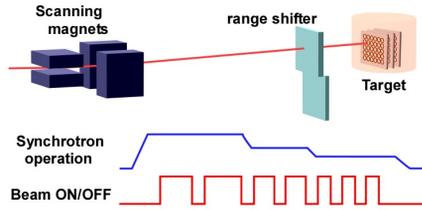


Figure 3: The schematics of CS operation.

MATERIALS AND METHODS

Pencil Beam Model

In 3D irradiation with pencil beam scanning, the prescribed dose distribution is realized by superposing the dose of individual pencil beams d according to their weights w optimized in treatment planning. The x - and y -coordinates denote the lateral and orthogonal directions, respectively, and the z -coordinate denotes the direction parallel to the beam axis. For j th pencil beam, whose central axis is at $(x_j(z), y_j(z), z)$, the dose distribution delivered, $d_j(x, y, z)$, is split into three components, two components in transverse directions, $d_{x;j}(x, z)$ and $d_{y;j}(y, z)$, and one, $d_{z;j}(z)$, parallel to the beam direction, and represented as follows:

$$d_j(x, y, z) = d_{x;j}(x, z) d_{y;j}(y, z) d_{z;j}(z). \quad (1)$$

Here, $d_{x;j}(x, z)$ and $d_{y;j}(y, z)$ are the normalized Gaussian functions with standard deviations $\sigma_{x;j}(z)$ and $\sigma_{y;j}(z)$ representing the beam spread at a depth z , $d_{z;j}(z)$ is the planar-integrated dose at a depth z over the infinite x - y plane. To derive these values, i.e. $\sigma_{x;j}(z)$, $\sigma_{y;j}(z)$ and $d_{z;j}(z)$, for the pencil beam delivered in each scan technique, we used Monte Carlo simulation software PTSSim [4], which is a simulation code for particle therapy based on Geant4. We created a C++ library describing the scanning irradiation system developed at NIRS [1]. In the simulation, mono-energetic carbon ions having various energies were generated with initial beam width $\sigma_x = \sigma_y = 1$ mm just upstream of the scanning magnets. For RS, we generated 290 MeV/u carbon ions with various thicknesses of range shifter plates. For ES, we generated carbon ions with 74 different energies from 80 MeV/u to 290 MeV/u by an energy step, corresponding to a water equivalent range of 2 mm. For CS, we generated 140, 170, 200, 230, 260 and 290 MeV/u carbon ions, with several thicknesses of range shifter plates up to 3 cm. The simulated dose distribution, $d_j(x, y, z)$, are fitted with (1) to derive $\sigma_{x;j}(z)$, $\sigma_{y;j}(z)$ and $d_{z;j}(z)$ for the beam. These values are registered in the treatment planning system along with the saturation-corrected dose-mean specific energy, $z_{z;j}^*$, to predict the radiobiological RBE in mixed radiation fields of therapeutic carbon beams based

on microdosimetric kinetic model [5]. As examples, $d_{z;j}(z)$ and $\sigma_{x;j}(z)$ of pencil beams having the ranges of 45, 85 and 125 mm are shown in Fig. 4 for each scan technique.

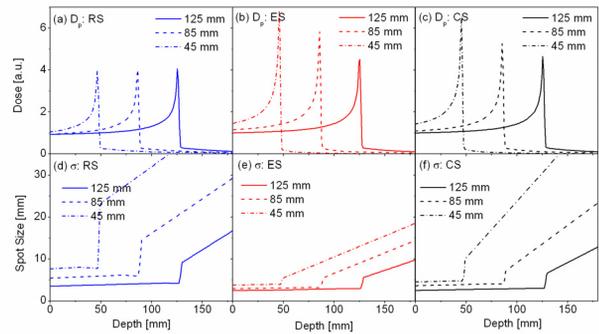


Figure 4: $d_{z;j}(z)$ (upper row) and $\sigma_{x;j}(z)$ (lower row) of pencil beams with range of 45, 85 and 125 mm for RS (left column), ES (middle column) and CS (right column).

Simulation

To evaluate the dose distribution realized with each longitudinal scan technique, we assumed three target volumes of $60 \times 60 \times 60$ mm³ at 45, 85 and 125 mm in a water phantom. The structure of the phantom was numerically modeled with voxels of size $\Delta x = \Delta y = \Delta z = 2.0$ mm. The clinical dose, defined by the product of the absorbed dose and the RBE, of 3.6 GyE is predicted for three targets with ES, RS and CS. In each plan, the Bragg peak positions were arranged on a regular, rectangular grid, with 2 mm spacing in both the beam and the transverse directions.

RESULTS AND DISCUSSION

Dose Distribution

Fig. 5 shows 2-D clinical dose distributions optimized for three targets with RS, ES and CS. The beam is delivered from left in the figures, the prescribed dose of 3.6 GyE was uniformly delivered over the target volume.

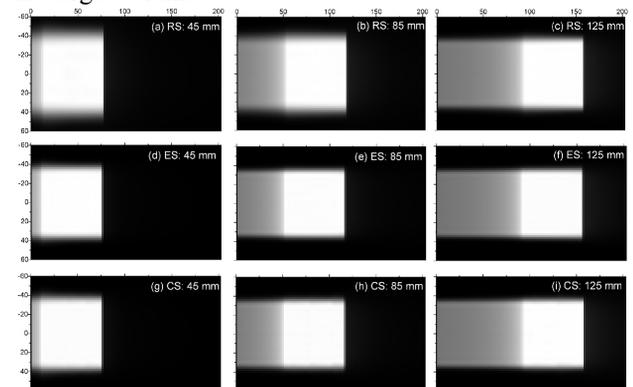


Figure 5: 2-D clinical dose distributions on x - z plane passing through the central beam axis delivered to the target at 45 (left column), 85 (middle column) and 125 mm (right column) with RS (upper row), ES (middle row) and CS (lower row).

Lateral Dose Profile

The lateral dose distributions along x -axis at a center of SOBP are shown in Fig. 6 for three targets. The lateral dose falloffs defined as the distance between 2.88 GyE (80% of the prescribed dose) and 0.72 GyE (20%), P_{80-20} , are 6.6, 5.7 and 5.0 mm in CS, while they are 11.4, 8.5, 5.9 mm in RS and 5.7, 4.8, 4.6 mm in ES, respectively. P_{80-20} for the target at 45 mm is twice the one at 125 mm in RS, while it is just 1.20 and 1.25 times greater in ES and CS, respectively. In Fig. 7, the spot size (σ) of the scanned pencil beam at the entrance of the target is plotted as a function of residual range for each scan technique. In RS, σ increases as the residual range decreases, i.e. the range shifter thickness increases, due to the multiple scattering of carbon ions within the range shifter plates. It reaches almost 12 mm for the beam having the residual range of 10 mm, i.e. range shifter thickness of 145 mm. In ES, σ increases with decreasing the residual range, while it reaches at most 7 mm for the beam with 80 MeV/u. In CS, σ shows a sawlike shape with discrete gaps at the ranges where beam energy changed. However, the deviation of σ in CS and ES is below 1.2 mm. These features of σ in CS make their lateral dose profiles close to the ones in ES.

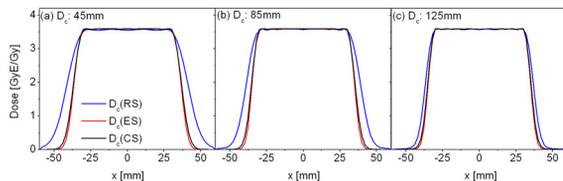


Figure 6: The lateral dose distributions along x -axis at a center of SOBP of the target at 45 (left column), 85 (middle column) and 125 mm (right column) with RS (blue curve), ES (red curve) and CS (black curve).

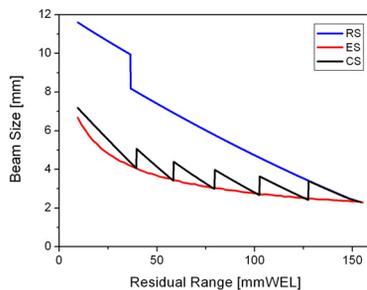


Figure 7: The spot size of the beam (σ) at the entrance of the target.

Depth Dose Profile

The depth-dose and depth-RBE profiles along z -axis are shown in Fig. 8 for three targets. For the target at 125 mm, each of three scan techniques provide almost the same dose/RBE profiles within the whole depth. The RBE values averaged over the target are 2.54, 2.60 and 2.53 in RS, ES and CS, respectively. However, the shallower the depth of the target, the greater the differences in dose/RBE profiles become. For the target at 45 mm, ES and CS provide similar profiles, while RS require greater

absorbed dose to achieve same clinical dose within the target. The RBE values are 2.73 and 2.72 in ES and CS, respectively, while 2.58 in RS. We plotted the ratio of carbon ions reaches around their range to the ones initially generated just upstream of the scanning magnets, F , in Fig. 9. In RS, F is almost constant at 0.48 due to the similar reaction rates of carbon ions within PMMA and water. In ES, F increases as the residual range decreases since the residual range is changed by the beam energy from the synchrotron. While F shows step-like shape with discrete gaps in CS, the discrepancy of F from ES is below 0.13. For the target at 45 mm, the dose contribution from carbon ions to that from secondary fragments within the target is 4.0% and 4.6% in ES and CS, respectively, while 12.5% in RS, making the RBE values higher in ES and CS comparing to RS.

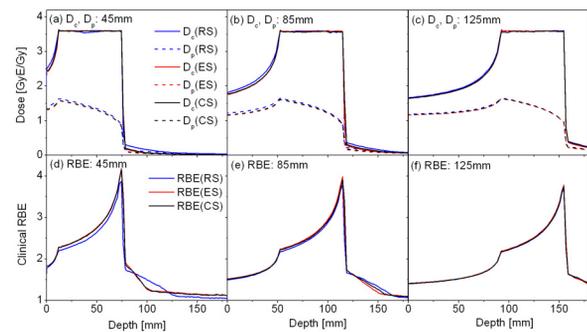


Figure 8: The depth-dose distributions along z -axis (upper row) and the depth-RBE (lower row) for three targets

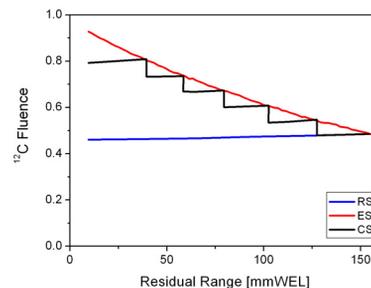


Figure 9: The fluence of primary ^{12}C ions at the range of the beam.

SUMMARY

A new longitudinal scan technique, CS, was investigated. CS can provide the dose distribution with superior lateral dose falloff and higher RBE comparing to RS, and comparable to ES.

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