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Dosimetric Impact of the Interplay Effect between the Proton Beam and Tumor Motion

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Introduction: Pencil beam scanning (PBS) is one of the main delivery techniques in proton therapy (PT). A narrow proton beam irradiates the tumor layer by layer, delivering dose to specific locations (spots) within each layer. However, PBS is highly sensitive to uncertainties, making the treatment of moving targets in PT especially challenging due to respiratory motion. The interplay effect, caused by the relative motion between the tumor and the scanning beam, can degrade the delivered dose and reduce treatment effectiveness. The main objective of this study is to accurately determine the dose received by moving tumors by quantifying the dosimetric impact of the interplay effect.
Material and Methods: A planning computed tomography (pCT), in which the treatment dose is planned, and a 4D-CT, consisting of eight CT images corresponding to different respiratory phases, were used to evaluate tumor motion. A stochastic model based on the compact HITACHI synchrotron was employed to predict the proton beam temporal structure. After determining the delivery time of each spot in the treatment plan, we can assign spots to each of the eight respiratory phases depending on the phase in which irradiation begins, and the patient's respiratory frequency. The frequency was varied between 5, 12 and 20 breaths per minute (bpm), and the initial respiratory phase was randomized for each treatment session/fraction across 100 simulations per frequency. The treatment plan dose was computed for each phase according to the spot distribution and summed on the pCT.
Results: Variability in delivery times and frequency influences layer deposition within the tumor (Figure 1), resulting in regions receiving higher doses (layers overlap, in red) or lower doses (layers are separated, in blue). Multiple (30) treatment sessions help mitigate the dosimetric impact of different starting respiratory phases (Figure 2). Higher frequencies reduce the interplay effect, especially when fewer (3) sessions are used, with standard deviations (SD) over 100 simulations in the tumor of ±0.43 Gy (5 bpm), ±0.20 Gy (12 bpm), and ±0.13 Gy (20 bpm).
Conclusion: Interplay between motion and dynamic beam delivery in PBS-PT degrades the dose distribution and can compromise the absorption of the prescribed dose in the tumor. Understanding the beam's temporal structure, which depends on the proton accelerator, and considering tumor motion, frequency, and number of treatment fractions, are critical for accurately determining the dose delivered to each tumor.

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