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Technical note

Optimization and evaluation of multiple gating beam delivery in a synchrotron-based proton beam scanning system using a real-time imaging technique

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Purpose: To find the optimum parameter of a new beam control function installed in a synchrotron-based proton therapy system.

Methods: A function enabling multiple gated irradiation in the flat top phase has been installed in a real-time-image gated proton beam therapy (RGPT) system. This function is realized by a waiting timer that monitors the elapsed time from the last gate-off signal in the flat top phase. The gated irradiation efficiency depends on the timer value, T_w. To find the optimum T_w value, gated irradiation efficiency was evaluated for each configurable T_w value. 271 gate signal data sets from 58 patients were used for the simulation.

Results: The highest mean efficiency 0.52 was obtained in $T_W = 0.2$ s. The irradiation efficiency was approximately 21% higher than at $T_W = 0$ s, which corresponds to ordinary synchrotron operation. The irradiation efficiency was improved in 154 (57%) of the 271 cases. The irradiation efficiency was reduced in 117 cases because the T_W value was insufficient or the function introduced an unutilized wait time for the next gate-on signal in the flat top phase. In the actual treatment of a patient with a hepatic tumor at $T_w = 0.2$ s, 4.48 GyE irradiation was completed within 250 s. In contrast, the treatment time of ordinary synchrotron operation was estimated to be 420 s.

Conclusions: The results suggest that the multiple gated-irradiation function has potential to improve the gated irradiation efficiency and to reduce the treatment time.

1. Introduction

Increasing numbers of proton therapy centers have adopted the spot-scanning technique. Spot scanning can potentially increase conformity to the target volume and modulates the dose more flexibly than the passive scattering approach. However, in beam scanning, the dose distribution may deteriorate under organ motions, such as respiratory or cardiac motions, during beam delivery [1–4]. Real-time four-dimensional radiotherapy, which includes beam gating [5–7] and beam tracking [8,9], has been realized in photon therapy to mitigate the dosimetric impacts of target motion. Gating [10–12] and tracking techniques [13,14] using external surrogates have also been reported in particle therapy. However, internal organ motions and the external surrogate signals of abdominal motion are not necessarily correlated during treatment [15]. Gated irradiation using internal fiducial markers based on real-time imaging is one of the best solutions in particle therapy.

In respiratory gated radiotherapy, reasonable gated irradiation efficiency is expected for clinical application. In carbon ion therapy system at National Institute of Radiological Science (NIRS), fast scanning technique including multi-energy irradiation with extended flat tops [16] and phase-controlled rescanning method

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[17] were realized to treat the mobile targets. By applying these techniques, reasonable treatment time can be achievable in NIRS carbon ion therapy. On the other hand, in the synchrotron for typical proton therapy system, beam current is relatively small compared with the carbon ion therapy system. In order to improve the gated irradiation efficiency with synchrotron based proton therapy, variable flat top phase synchrotron operation, described in the later section, has been applied. However, the gating signals change irregularly and sporadically under complex tumor motions [18] and, in some cases, poor recognition of the fiducial markers [19,20]. The resulting fluctuations in the gating signal can significantly reduce the gated irradiation efficiency in variable flat top phase synchrotron operation [21]. To improve the gated irradiation efficiency, we have developed a real-time-image gated proton beam therapy (RGPT) system [22–24] which has a new function, called the multiple gated-irradiation function [20,25]. The combination of variable flat top phase operation and multiple gated-irradiation function was realized in the first in RGPT. This technique is the new approach to improve the gated irradiation efficiency.

Since the gated irradiation efficiency depends on the wait time T_w in multiple gated-irradiation function, we need to optimize this setting. As an initial step to use this new control function, we have decided to start RGPT with fixed T_w operation to make the treatment procedure simple. The purpose of this study is to evaluate the efficiency of gated irradiation and to find the optimum T_w which can improve the mean efficiency on the average.

2. Materials and methods

2.1. Real-time-image gated proton beam therapy (RGPT) system

Fig. 1 shows the RGPT system using a synchrotron-based accelerator. As indicated in the figure, a proton scanning nozzle, flat panel detectors, and X-ray tubes are installed in a rotating gantry. The real-time imaging system tracks the internal fiducial markers similarly to photon therapy and is based on the same concept [5]. The three-dimensional position of a fiducial marker located near the tumor is calculated from two fluoroscopic images obtained from orthogonal directions. The field of view is sized 21.6 cm × 21.6 cm at the isocenter plane. The image acquisition rate can be selected from discrete values ranging from 0.1 to 30 Hz. When the coordinates of the internal fiducial marker are within the gating window predefined in the treatment planning, the gate-on signal is transmitted from the real-time imaging equipment to the beam irradiation controls. The typical size of the gating window in three directions (right-left, antero-posterior, and cranio-caudal) is ±2 mm.

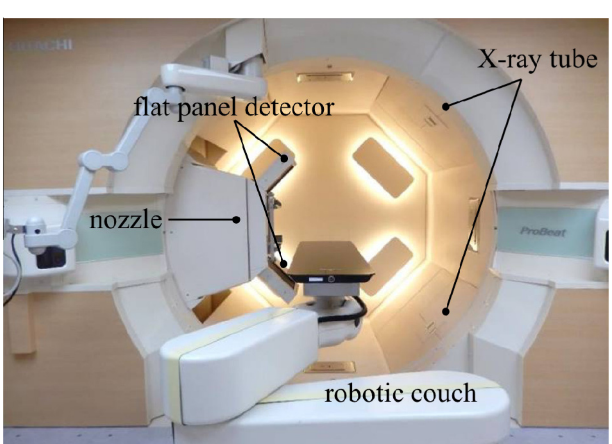

Fig. 1. Overview of the real-time-image gated proton beam therapy (RGPT) system.

2.2. Function of multiple gated irradiation

The basic operation cycle of a synchrotron comprises an acceleration phase, a deceleration phase, and a flat top phase. In conventional operation, these phases are repeated at fixed durations. Unwanted synchronizations of the respiratory/cardiac motions and synchrotron operation pattern can degrade the efficiency of the respiratory-gated irradiation [25]. To improve the gated irradiation efficiency, a function enabling variable flat top phases has been reported [10]. The variable flat top phase operation has two characteristic functions: the first function waits for the first gate-on signal while maintaining the beam energy after the acceleration phase; the second decelerates the protons after gate-off during the flat top phase. In this way, unwanted synchronization of respiratory/cardiac motion and synchrotron operation can be avoided. However, the gate signals based on the internal markers are sensitive to slight changes in the identified marker positions near the gate boundaries, as shown in Fig. 2. In this case, the synchrotron decelerates the protons before they can be extracted in sufficient numbers due to frequent changes of the gate signals.

To improve the irradiation efficiency of the above gating technique, we have developed a novel function that enables multiple gated irradiations in the flat top phase [21,22]. This function is realized by a waiting timer that monitors the time elapsed since the previous gate-off signal in the flat top phase. As shown in Fig. 2, the beam irradiation can be promptly restarted without deceleration when the elapsed wait time is shorter than the predefined limit time (T_w). The gated irradiation efficiency can be improved by applying this function.

2.3. Evaluation of the gated irradiation efficiency

The gated irradiation efficiency will depend on the T_w value. Beam irradiation profiles at typical T_W values are shown in Fig. 3. In this example, the efficiency of the multiple gated irradiation is higher at T_W of 0.2 and 0.5 s than at T_W = 0.0 s but is reduced at T_W = 1.0 s because of unutilized wait times. Hence, the optimum T_W should be identified prior to starting the RGPT. Therefore, we varied the T_w value and evaluated the gated irradiation efficiency by simulating the actual time-series data of the gate signals obtained from a photon real-time tumor-tracking radiotherapy (RTRT) system. The evaluation is detailed below.

2.3.1. Clinical data of gate signals for the evaluation

The RTRT system records a log during X-ray fluoroscopy in the treatment session. The log file includes three-dimensional marker positions and the status of the gate signal (gate-on/gate-off) at 33 ms intervals. The log files for the evaluation were randomly chosen from lung cancer patients previously treated by photon RTRT. Some of the datasets included unidentified spike artifacts caused by unusual tumor motions such as coughing. These datasets were discarded. To simulate the usual beam gating conditions, log data with motion ranges less than 5 mm were also discarded. One dataset per patient was randomly chosen from one treatment day. Consequently, the evaluation dataset contained 271 gate signal data from 58 patients. The number of datasets per patient ranged from 1 to 25 (median = 4). Data collection times were 125 ± 81 s (range 30–492 s), and the duty cycle of the gated irradiation, defined as the ratio of beam-on frames to the total frames, was 0.51 ± 0.18 (range 0.11–0.98). Duty cycles were relatively large with small motions of the internal marker, as previously reported [26].