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Original paper

Usefulness of a new online patient-specific quality assurance system for respiratory-gated radiotherapy

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ABSTRACT

Purpose: The accuracy of gated irradiation may decrease when treatment is performed with short "beam-on" times. Also, the dose is subject to variation between treatment sessions if the respiratory rate is irregular. We therefore evaluated the impact of the differences between gated and non-gated treatment on doses using a new online quality assurance (QA) system for respiratory-gated radiotherapy.

Methods: We generated dose estimation models to associate dose and pulse information using a 0.6 cc Farmer chamber and our QA system. During gated irradiation with each of seven regular and irregular respiratory patterns, with the Farmer chamber readings as references, we evaluated our QA system's accuracy. We then used the QA system to assess the impact of respiratory patterns on dose distribution for three lung and three liver radiotherapy plans. Gated and non-gated plans were generated and compared.

Results: There was agreement within 1.7% between the ionization chamber and our system for several regular and irregular motion patterns. For dose distributions with measured errors, there were larger differences between gated and non-gated treatment for high-dose regions within the planned treatment volume (PTV). Compared with a non-gated plan, PTV $D_{95\%}$ for a gated plan decreased by −1.5% to −2.6%. Doses to organs at risk were similar with both plans.

Conclusions: Our simple system estimated the radiation dose to the patient using only pulse information from the linac, even during irregular respiration. The quality of gated irradiation for each patient can be verified fraction by fraction.

1. Introduction

Respiratory motion can affect the accuracy of external beam treatment delivery to the thorax and abdomen. Large margins are thus required to compensate for targeted respiratory motion, which may increase the dose to normal tissue to the extent that it limits the dose to the target. One way to reduce the impact of respiratory motion during radiotherapy is to use respiratory gating techniques [1]. Such usage can decrease the dose to organs at risk (OARs), allowing reduction of the clinical target volume margins and allow an appropriate target dose. A respiratory gating system requires external devices or markers that generate signals to turn the beam on or off [2–5]. Although the potential advantage of the respiratory-gated treatment technique has been demonstrated [1,3,6–8], clinical implementation of this technique requires a thorough understanding of its limitations.

Respiratory patterns in patients may be variable in magnitude, period, and regularity during treatment sessions [9–12]. Repeated irradiation with low-grade monitoring units are likely to increase dose errors during gated irradiation [13–15]. Weibert et al. [14] investigated the beam characteristics for a duty cycle (the ratio of the "beam-on time" to the total treatment time) under gating. They found no statistically significant difference in depth-dose curves and beam profiles even in 5% duty cycles of realistic respiration frequencies. They showed, however, that the absolute dose changed significantly (> 10%), leading to clinically relevant underdoses for smaller duty cycles. Freislederer et al. investigated the impact of the gating window size [13]. The dose difference between gated and ungated treatments increased with decreasing window size. Hence, with use of a 10% gating window during a 6-s period, the dose difference was > 2%. Evans et al. investigated the characteristics of an Elekta linac (Elekta,

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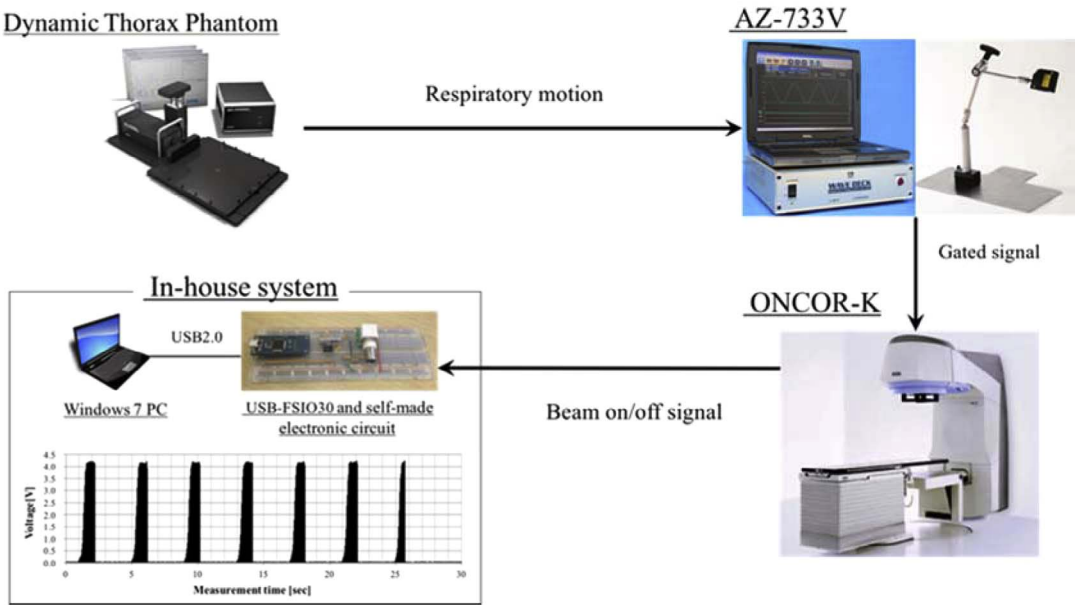

Fig. 1. Configuration of the linac, gating system, motion platform, and our quality assurance (QA) system.

Stockholm, Sweden) equipped with gating [15]. The dose difference between gated and ungated treatments increased depending on the "beam-on" time. The published literature shows that the accuracy of gated irradiation would decrease if gated irradiation were performed repeatedly with a short "beam-on" time [13–15]. Every start-up process of "beam-on" is accompanied by a particular uncertainty because of the linac's transient response [14].

Patients' respiratory patterns often change during intra-fractional and inter-fractional treatment. Thus, gated irradiation with short "beam-on" times is still sometimes unavoidable. There would be a trade-off when choosing a smaller gating window to reduce margins as much as possible as it would enhance dosimetric errors. Lengthening the "beam-on" time by increasing the gating window width could increase the volume of normal tissue being irradiated, with higher doses to the internal margins for the internal target volume. There have been several strategies available to make respiration more regular. For respiratory gating, a visual/audio feedback system has been employed [9,12,16,17]. Several studies suggest that a visual/audio feedback system would improve the reproducibility of respiration [9,12,16,17]. but it is dependent on the patient's ability to cooperate. Neicu et al. [12] reported on the difficulty of respiratory coaching for lung cancer patients. They noted that breath coaching was well tolerated by all volunteers, and the reproducibility of their breathing patterns improved. Nevertheless, four out of 33 patients (12%) could not be coached at all because of their medical conditions or they had difficulty following the instructions [12]. Thus, gated irradiation with short "beam-on" times is sometimes unavoidable, and the impact of these gated beams on the accuracy of the dose delivered needs to be addressed with the specific patient. For quality assurance of dated irradiation during treatment sessions, it would be important to understand the accuracy of the delivered doses over the treatment course.

Recently, multi-institutional clinical trials have been performed worldwide, and the quality of the contoured planning has been checked regarding whether participants achieved similar levels of information before the initiation of the trials and during the trials themselves [18–23]. In addition, a dosimetry audit is commonly performed to check the level of irradiation before initiating the trial [24,25]. In previous clinical trials, the quality of irradiation has not been evaluated during the actual treatment in individual patients, with the complexity of gated irradiation possibly accounting for the variation in patients' outcomes. The importance of in vivo dosimetry has been increasing, with several publications addressing in vivo dosimetry [26–28]. For direct measurements using in vivo dosimetry to assess the irradiation, gantry-attached in vivo dosimetry tools—the DAVID system (PTW-Freiburg, Germany) and Delta4 Discover (ScandiDos AB, Uppsala, Sweden)—have shown potential to enable users to monitor the administered dose [29–31]. These systems, however, have not been used to monitor gated treatments, and the cost of these detectors might make their installation prohibitive.

First, we designed and developed a simple online quality assurance (QA) system to verify the doses of an individual patient's gated radiotherapy. We focused on the pulse information from the linac, which would correspond to the radiation output. Thus, we investigated the relation between dose at 10 cm depth and the pulse information measured using the QA system with an electronic circuit during gated irradiation so we could generate a model of the conversion between the number of pulses and the dose. We evaluated our QA system's accuracy for dose estimation. Second, we evaluated the effectiveness of the QA system to understand the accuracy of the delivered doses over the treatment course during gated radiotherapy. Using this system, we investigated the impact of patients' respiratory patterns on dose distribution for lung and liver tumors. The errors in radiation output for several respiratory patterns were measured by our system. Subsequently, the dose distributions were compared between non-gated irradiation and gated irradiation, with the outputs including the measured errors.

2. Materials and methods

2.1. QA system for gating irradiation

We focused on the irradiation pulse from the linac to estimate the dose error in respiratory-gated irradiation. As shown in Fig. 1, a USB-FSIO30 (Km2Net Co, Ltd, Hiroshima, Japan) was used to obtain the pulse from the linac, which includes an input/output circuit board using the USB interface. The USB-FSIO30 can perform digital input/output, 10-bit A/D conversion, analog input, and pulse width modulation control. The USB-FSIO30 was connected to a personal computer (NEC PC-LS550DS6L, Core™ 2 i5-M460 processor 2.67 GHz, 4 GB memory; NEC Corporation, Kawasaki, Japan) that used a Windows 7 operating system (Microsoft, Inc., Redmond WA, USA) by a USB 2.0 port. We implemented a simple oscilloscope software program with a