2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

A Practical and Simple Method to Estimate Beam-on Delay In Respiratory-Gated Radiotherapy

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ABSTRACT

Purpose: To develop a practical and simple method for estimating beam-on delay associated with respiratory-gated radiotherapy and validating the accuracy of the estimated delays.

Methods: A respiratory monitoring system (AbchesET, APEX Medical, Japan) tracked the motion of the phantom and delivered gating signals to a linear accelerator (VersaHD, Elekta, Sweden) in real time. Two beams of 6MV and 6FFF and the minimum and maximum amplitude-based gating windows (20 and 80%) were used to acquire gating durations (GD) and delivered MU numbers for each gating window. The calculated beam-on delays were acquired from an equation using GD and MU. To obtain the reference beam-on delays, a rod with a ball-bearing (BB) marker attached at the end was placed on the moving phantom and captured the moment the BB entered 50% amplitude using a megavoltage imager. The velocity of the BB was 86.1 pixels per second.

Results: The delay averaged from the maximum (80%) and minimum (20%) gating windows was close to the reference. The calculated (reference) beam-on delays were 230 (244) ms and 80 (95) ms for 6MV and 6FFF beams, respectively. The calculated delays were underestimated by approximately 15 ms compared with the references.

Conclusion: This study demonstrated an experimental and practical method to estimate beam-on delay with acceptable accuracy. Because this method does not require substantial effort or cost typically needed for direct beam-on delay measurements, it could be suitable for periodic machine quality assurance and for evaluating specific treatment cases in a clinical setting.

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INTRODUCTION

Respiratory motion remains a major source of geometric uncertainty in thoracic and abdominal radiotherapy. Respiratory-gated radiotherapy reduces this uncertainty, but this relies on communication between the respiratory monitoring system and the linear accelerator resulting in an inherent time delay between the gating signal and actual beam initiation or termination. The AAPM Task Group 76 (TG-76) report[1] recommends evaluating the temporal characteristics of respiratory gating systems, including beam-on and beam-off delays, as part of commissioning and periodic quality assurance (QA) because these delays can influence treatment accuracy. Although several practical methods[2-4] have been proposed to implement the TG-76 recommendation for time delay evaluation, most require dedicated equipment, such as an MV imager, film, and motion phantoms, or rely on complex analyses of log files or imaging data. Although these methods provide accurate measurements, they are often time-consuming and costly to perform on a daily or weekly basis. Therefore, in this study, we propose a simple method for evaluating the time delay using only a respiratory monitoring system, which is routinely available in institutions performing respiratory-gated radiotherapy.

METHODS AND MATERIALS

A respiratory monitoring system (AbchesET, APEX Medical, Japan) was installed on a linear accelerator (VersaHD, Elekta, Sweden), and the minimum (20%) and maximum (80%) achievable gating windows were selected as shown in figure 1. For each gating window, the beam turned on for five cycles, and the cumulative gating duration time (T) provided by the monitoring system and the cumulative delivered monitor units (MU) displayed on the treatment console were recorded. Measurements were performed using 6 MV and 6 MV FFF photon beams with a fixed dose rate (DR) of 400 MU/min.

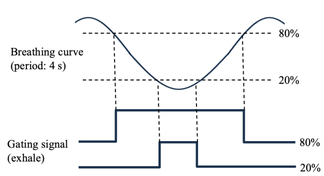

Figure 1. Definition of gating windows at amplitude gating mode

To estimate the beam-on time delay (T_d), a simple equation was derived under the assumption of a constant DR as shown in figure 2. Actually, DR is not constant because of the beam on-off. At wider gating windows, the error introduced by DR variation is relatively small, whereas the T_d/T ratio is reduced, resulting in greater uncertainty in the estimated T_d. The opposite is true for narrower gating window. Therefore, the final T_d value was determined as the average of T_d values from 80% and 20% gating windows.

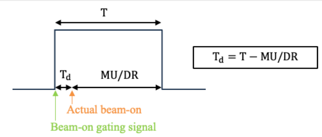

Figure 2. The estimation of beam-on delay using T, MU, and DR values

To obtain the reference beam-on delays, a rod with a ball-bearing (BB) marker attached at the end was placed on the moving phantom (figure 3) and captured the moment the BB entered 50% amplitude using a megavoltage imager. The velocity of the BB was 86.1 pixels per second, and the pixel pitch was 0.252 mm at the isocenter. The reference T_d was determined from the velocity and displacement of the BB based on its actual trajectory observed in the images (figure 4).

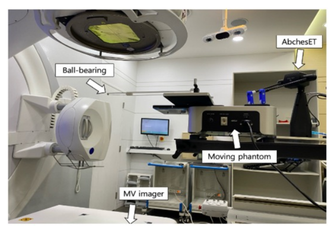

Figure 3. Experimental setup for measuring the reference beam-on delay

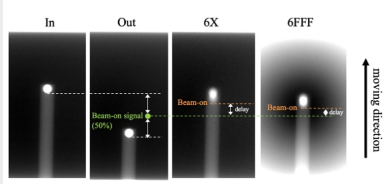

Figure 4. MV image analysis to measure the beam-on delay

RESULTS

The estimated (reference) T_d values were 230 (244) ms and 80 (95) ms for 6MV and 6FFF beams, respectively, and the deviations between the estimated and references were nearly constant (14–15 ms) regardless of the magnitude of the beam-on delay. The data obtained to estimate the beam-on delay was summarized in Table 1.

Table 1. Comparison of estimated and reference beam-on delays

Beam	Gating		MU	Time delay (ms, T_d)		
	Window	T (ms)		Estimated	Reference	Deviation
6 MV	80%	3856	24.96	230	244	-14
	20%	1148	5.34			
6 MV FFF	80%	3838	24.7	80	95	-15
	20%	1146	7.46			

DISCUSSION

The beam-on delay evaluation method proposed in this study can be implemented using the same monitoring system employed for gated radiotherapy. Compared with previously reported methods based on MV imaging or other dedicated measurement devices, this approach substantially reduces both the time and cost required for the beam-on delay evaluation. Consequently, it can be readily incorporated into routine QA procedures, such as daily QA, enabling more proactive management of patient safety of gated radiotherapy.

This study has two limitations. First, the proposed method is an indirect calculation based on the assumption of a constant DR, which inherently limits its accuracy. Therefore, periodic cross-validation using direct measurement methods, such as MV imaging, may be necessary to verify the accuracy of the calculated beam-on delay. Second, the proposed method was validated on only a single linear accelerator and a single respiratory-monitoring system. Additional studies are required to evaluate its applicability and performance across treatment systems from other vendors. In addition, the monitoring system should be able to provide gating duration with millisecond-level accuracy.

CONCLUSIONS

This study demonstrated an experimental and practical method to estimate beam-on delay with acceptable accuracy. Because this method does not require substantial effort or cost typically needed for direct beam-on delay measurements, it could be suitable for periodic machine quality assurance and for evaluating specific treatment cases in a clinical setting.

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