学位論文 博士(医科学)甲

Evaluation of the latency and the beam characteristics of a respiratory gating system using an Elekta linear accelerator and a respiratory indicator device, Abches

(Elekta 社リニアックとアブチェスを使用した新たな呼吸同期照射における遅延時間および基礎的ビーム特性の評価)

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Technical Note: Evaluation of the latency and the beam characteristics of a respiratory gating system using an Elekta linear accelerator and a respiratory indicator device, Abches

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Purpose: To evaluate the basic performance of a respiratory gating system using an Elekta linac and an Abches respiratory-monitoring device.
Methods: The gating system was comprised of an Elekta Synergy linac equipped with a Response^{TM} gating interface module and an Abches respiratory-monitoring device. The latencies from a reference respiratory signal to the resulting Abches gating output signal and the resulting monitor-ion-chamber output signal were measured. Then, the flatness and symmetry of the gated beams were measured using a two-dimensional ionization chamber array for fixed and arc beams, respectively. Furthermore, the beam quality, $TPR_{20,10}$, and the output of the fixed gated beams were also measured using a Farmer chamber. Each of the beam characteristics was compared with each of those for nongated irradiation.
Results: The full latencies at beam-on and beam-off for 6-MV gated beams were 336.4 ± 23.4 ms and 87.6 ± 7.1 ms, respectively. The differences in flatness between the gated and nongated beams were within 0.91% and 0.87% for the gun-target and left-right directions, respectively. In the same manner, the beam symmetries were within 0.68% and 0.82%, respectively. The percentage differences in beam quality and beam output were below 1% for a beam-on time range of 1.1–7 s.
Conclusion: The latency of the Elekta gating system combined with Abches was found to be acceptable using our measurement method. Furthermore, we demonstrated that the beam characteristics of the gating system using our respiratory indicator were comparable with the nongated beams for a single-arc gated beam delivery. © *2017 American Association of Physicists in Medicine* [https://doi.org/10.1002/mp.12664]

Key words: delay time, flatness, gated radiotherapy, respiratory motion, symmetry

1. INTRODUCTION

A respiratory gating system is a useful solution for respiratory motion management in radiotherapy.[1] The gating strategy involves the administration of radiation within a particular stage of the patient's breathing cycle known as the gating window. The gating-window position and width within the respiratory cycle are determined by monitoring the respiratory motion, using either an external respiration signal or internal fiducial markers. Currently, several respiratory gating systems employing optical sensors are commercially available, such as the Real-time Position Management (RPM; Varian Medical Systems, Palo Alto, CA, USA), AZ-733V (Anzai Medical, Tokyo, Japan), and Catalyst (C-RAD AB, Uppsala, Sweden) systems.

Recently, the authors' group developed a patient-controlled respiratory device based on visual confirmation, where two fulcrums were placed on the patient's abdomen and chest to measure thoracoabdominal surface displacements.[2] This device was subsequently commercialized under the name "Abches" (APEX Medical Inc, Tokyo, Japan), and has been used in many facilities as a breath-hold monitor. In addition, several user reports have been published.[2,3] Gated radiotherapy using an Elekta linear accelerator (linac) with Abches via an Elekta Response^{TM} (Elekta AB, Stockholm, Sweden) gating control interface is feasible. The Response^{TM} interface allows the linac to pause and resume the delivery of radiation by controlling high-voltage pulses using validated third-party external respiratory surrogate systems.

As an Elekta gating system, the combination of the above-mentioned Catalyst system with the Response^{TM} interface has already been investigated.[4,5] However, no reports indicating the gating performance of the Abches device when used in conjunction with Response^{TM} have been published. Furthermore, the latency measurement procedure of the Elekta gating system has not been well documented; this is particularly noteworthy as a previous latency report showed significant uncertainties.[5]

Therefore, this study evaluates the basic performance of a respiratory gating system comprised of an Elekta linac and an Abches respiratory-monitoring device. The latencies are measured, along with the flatness (F), symmetry (S), and quality of the gated beams. The tissue-phantom ratio (TPR) is also investigated at different depths and for different photon energies. The beam characteristics are compared against those for nongated irradiation.

2. MATERIALS AND METHODS

2.A. Elekta-gated system with Abches

Figure 1 shows a signal flow diagram for gated beam delivery using an Elekta Synergy® linac with Abches, a patient-controlled respiratory device based on visual confirmation. The Abches device is comprised of a main body, an indicator panel, and two fulcrums. One fulcrum is placed on the patient's abdomen while the other is placed on the chest to measure the thoracoabdominal surface displacements. The pointer on the indicator panel moves in accordance with the fulcrums during respiration. A mirror is attached to the patient's head, thereby allowing the patient to monitor the pointer position correlating to the respiratory motion. Additional details regarding the Abches device are presented in our previous report.[2] The respiratory signal yielded by Abches is digitized by a workstation, and a binary gating signal is then fed into an Elekta Response™ module. The respiratory gating level (gating window) is determined based on the patient's respiration amplitude, as displayed on the workstation. The Response™ module controls the high-voltage pulses inside the linac, thereby generating gated high-energy photon beams.

2.B. Measurement of gating system latency

Figure 2 shows the measurement set-up used in this study to evaluate the latency and beam characteristics of the respiratory gating system shown in Fig. 1. This system was comprised of a Dynamic Thoracic Phantom (CIRS, Virginia, USA) as a respiratory-moving phantom, the Abches device, and a small photosensor. A metal plate was attached to one of the Abches fulcrums. Further, the moving phantom was continuously driven in the longitudinal direction by a sine-wave function to create a free breathing model, having a peak-to-peak amplitude of 2 cm and a 4-s cycle. The gating window was set to between 0% (maximum exhalation) and 50% phantom expansion, where 100% corresponds to the maximum inhalation. The photosensor generated a reference respiratory signal whenever the metal plate interrupted the light propagation. Note that the photosensor and metal plate, having a detection cycle of 30 ms, provided a more accurate reference respiratory signal than the internal respiratory signal generated in the Abches software. Using a TDS 3034C (Tektronix, Beaverton, USA) multichannel storage oscilloscope, the latencies were measured from the reference respiratory signal to the Response™ module output signal, and from the Response™ module output signal to the monitor chamber signal during beam-on and beam-off, with a gantry angle of 0° and photon energies of 6 and 10 MV. The measurements were repeated ten times. In addition, for all measurements, the accelerator gun hold-on time was extended to 6.5 s.[4]

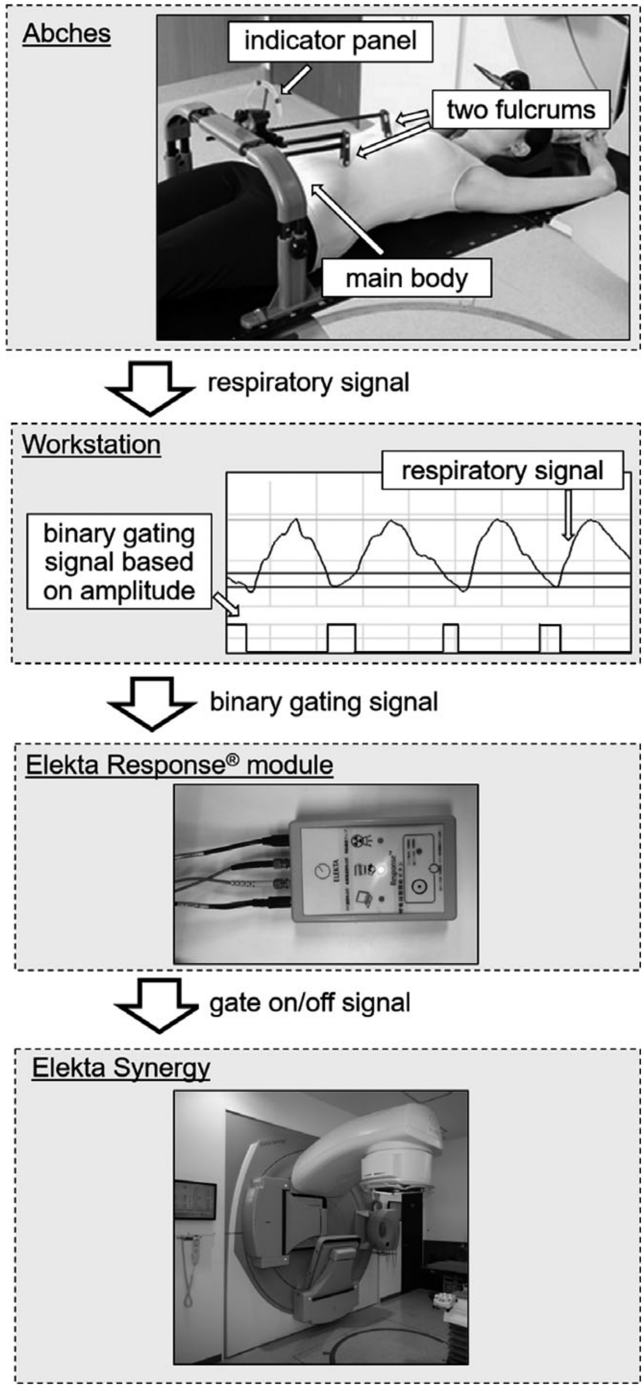

Fig. 1. Signal flow diagram for gated beam delivery using Elekta Synergy® linac with Abches respiratory-monitoring device. Abches is a patient-controlled respiratory device based on visual confirmation, comprised of a main body, indicator panel, and two fulcrums. The fulcrums are placed on the patient's abdomen and chest to measure the thoracoabdominal surface displacements. The resultant respiratory signal yielded by the Abches device is digitized by a workstation; then, a binary gating signal is fed into an Elekta Response™ module. The Response™ module controls the high-voltage pulses inside the linac, thereby generating gated high-energy photon beams.

2.C. Evaluation of gated beam characteristics

The differences between the gated and nongated beams were evaluated in terms of the (a) F, (b) S, (c) beam quality,

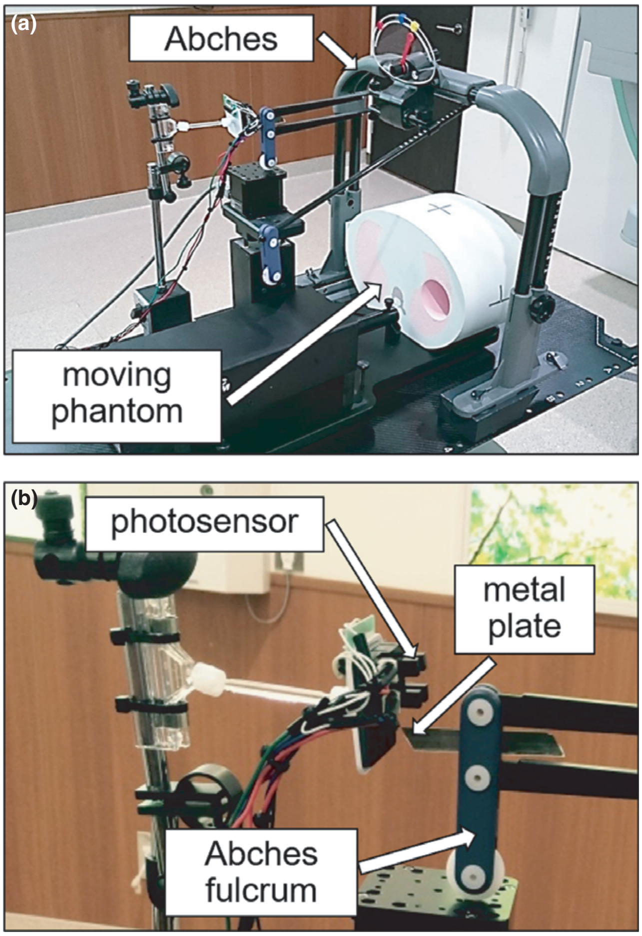

FIG. 2. Measurement set-up for evaluating latency and beam characteristics of respiratory gating system in Fig. 1. (a) The system was comprised of a respiratory-moving phantom, the Abches device, and a small photosensor. (b) A metal plate was attached to an Abches fulcrum. The photosensor generated a reference respiratory signal every time the metal plate interrupted the light propagation in the photosensor. The photosensor and metal plate, having a detection cycle of 30 ms, provided a more accurate reference respiratory signal than the internal respiratory signal generated in the Abches software. [Color figure can be viewed at wileyonlinelibrary.com]

and (d) beam output characteristics. For the *F* and *S* evaluation, the measurements were performed in the gun-target (GT) and left-right (LR) directions using an OCTAVIOUS 729 (PTW, Freiburg, Germany) two-dimensional ionization detector, with beam-on times of 1.1, 2.0, 3.0, 4.0, 5.0, and 7.0 s, and a beam-off-time of 2.0 s. First, fixed gated beams from a 0° gantry angle were delivered with a field size of 20 × 20 cm^2, a dose of 200 monitor units (MU), a 500-MU/min dose rate, and a 6-MV photon energy. In addition, to evaluate the volumetric modulated arc radiotherapy (VMAT) delivery, single-arc beams in a clockwise direction from 180.1° to 179.9° were delivered, with a field size of 16 × 16 cm^2, a 500-MU dose, and a 6-MV photon energy. One of three dose rates, i.e., 500, 250, or 125 MU/min, was employed. The measurements with the arc beams were performed by mounting the OCTAVIOUS ionization detector on the linac gantry head. Each measurement was repeated five times. The differences relative to the nongated delivery case were evaluated using the following equations:

$$F_{diff}(\%) = F_{gated} - F_{non-gated}, \tag{1}$$

$$S_{diff}(\%) = S_{gated} - S_{non-gated}, \tag{2}$$

where the *diff*, *gated*, and *nongated* subscripts indicate the difference, gated, and nongated values, respectively.

Additionally, we evaluated the tissue-phantom ratio at depths of 20 and 10 cm ($TPR_{20,10}$) using a type-30013 Farmer chamber (PTW, Freiburg, Germany) for photon energies of 6 and 10 MV. Here, the gated beams were delivered with a field size of 10 × 10 cm^2, a 200-MU dose, a 500-MU/min dose rate, and identical beam-on and beam-off times, as employed in the *F* and *S* measurements. Again, each measurement was repeated five times. We evaluated the percentage difference relative to nongated delivery using the following equation:

$$TPR_{diff}(\%) = \left(\frac{TPR_{gated} - TPR_{non-gated}}{TPR_{non-gated}}\right) \times 100. \tag{3}$$

We also evaluated the 6- and 10-MV beam output at a phantom depth of 10 cm. We evaluated the percentage difference relative to nongated delivery using the following equation:

$$Output_{diff}(\%) = \left(\frac{Output_{gated} - Output_{non-gated}}{Output_{non-gated}}\right) \times 100. \tag{4}$$

3. RESULTS

3.A. Latency evaluation

Figure 3 shows comparisons of the Abches reference signals, the Response™ module output signals, and the dose monitor signals measured by the storage oscilloscope for (a) the first gated pulse and (b) the subsequent gated pulse. The latency was calculated between two corresponding points on both plots, each giving half the maximum height. The latency from the Response™ module output signal to the dose monitor signal for the first gated pulse was considerably larger than that for the subsequent gated pulse. Thus, the first gated pulse was eliminated from the latency analysis.

Table I presents further details of the measured latencies. It was found that the beam-on latency was dominated by the linac. In addition, the linac-induced beam-on latency was greater than the linac-induced beam-off latency. On the other hand, the beam-off latency was dominated by the Abches device. Noteworthy variations were observed between the beam-on and beam-off latencies originating from the Abches device. The larger beam-on latency was presumably caused by busier communication, including interlock monitoring between the Abches device and the Elekta Response™ module.

3.B. Beam characteristics

Figure 4 shows the plots of the differences in (a) *F*, (b) *S*, (c) the beam quality, i.e., $TPR_{20,10}$, between the fixed gated

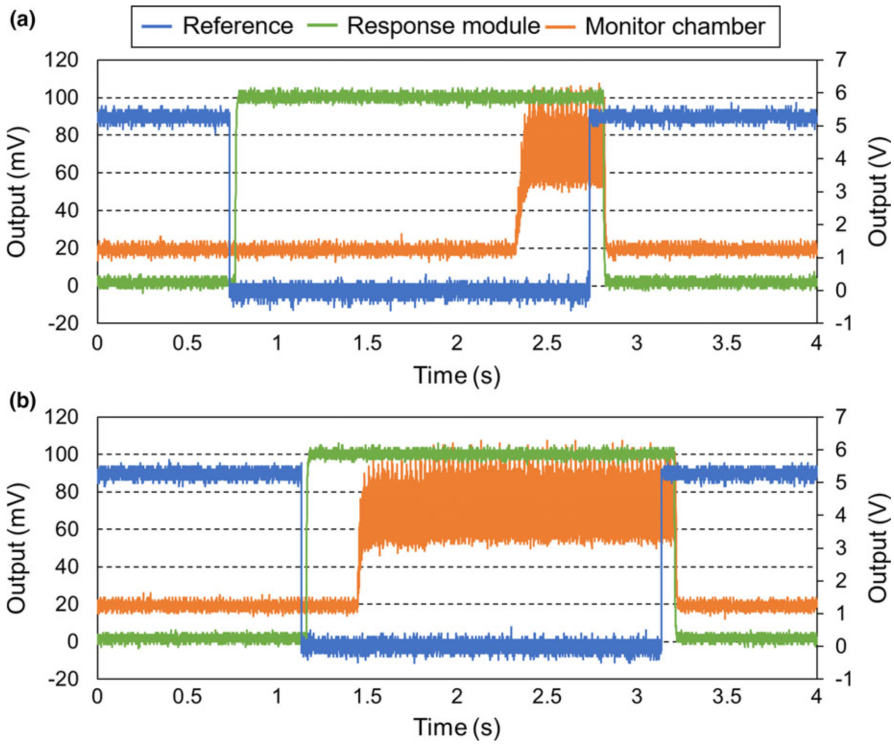

FIG. 3. Comparisons of Abches reference signals, Response^{TM} module output signals, and dose monitor signals measured by storage oscilloscope for (a) first and (b) subsequent gated pulses. The latencies were calculated between two corresponding points, each giving half the maximum height. The latency from the Response^{TM} module output signal to the dose monitor signal for the first gated pulse was considerably larger than that for the subsequent gated pulse.

and nongated beams, and (d) the beam output; these differences were calculated relative to the nongated beam results using Eqs. (1)–(4). In the figure, each error bar represents the standard deviation calculated from five repeated measurements. As expected, the differences were rapidly reduced when the beam-on time was extended. The difference in F was within 0.35% and 0.67% in the GT and LR directions, respectively. Similarly, the difference in S was within 0.59% and 0.73% in the GT and LR directions, respectively. The percentage differences in beam quality and beam output were below 1% for a beam-on time range of 1.1–7 s.

Table II lists the beam F and S values for each nongated single-arc beam. Hence, it is apparent that the beam flatness and symmetry improved as the dose rate increased.

Figure 5 depicts plots of the differences between the gated and nongated beams during 6-MV single-arc delivery under three constant dose rates of 500, 250, and 125 MU/min, where F and S are shown in the (a, c, respectively) GT and (b, d, respectively) LR directions. Here, the differences were calculated relative to the nongated beams using Eqs. (1) and (2). For the 500-MU/min dose rate, the difference in F was within 0.91% and 0.87% for the GT and LR directions, respectively. In the same manner, the beam S was within 0.68% and 0.82% for the GT and LR directions, respectively. On the other hand, for the 250- and 125-MU/min dose rates, the difference in F was within 0.49% and 0.51% in the GT and LR directions respectively, whereas the difference in S was within 0.28% and 0.24% in the GT and LR directions, respectively. Again, each error bar represents each standard deviation calculated from five repeated measurements. It was observed that the standard deviations for the data in the LR direction were considerably less than those in the GT direction. However, the cause of this discrepancy is currently

TABLE I. Separately measured latencies from reference respiratory signal to Response^{TM} module output signal, and from Response^{TM} module output signal to monitor chamber signal during beam-on and beam-off, with photon energies of 6 and 10 MV.

		Latency (ms, average ± standard deviation)	
		6 MV	10 MV
Beam-on	Reference signal to Response^{TM} module output	43.3 ± 12.7	40.3 ± 15.2
	Response^{TM} module output to monitor chamber	293.2 ± 22.5	188.8 ± 7.7
	Total	336.4 ± 23.4	229.1 ± 15.0
Beam-off	Reference signal to Response^{TM} module output	79.8 ± 7.1	76.4 ± 7.8
	Response^{TM} module output to monitor chamber	7.8 ± 0.8	2.8 ± 1.8
	Total	87.6 ± 7.1	79.2 ± 7.5

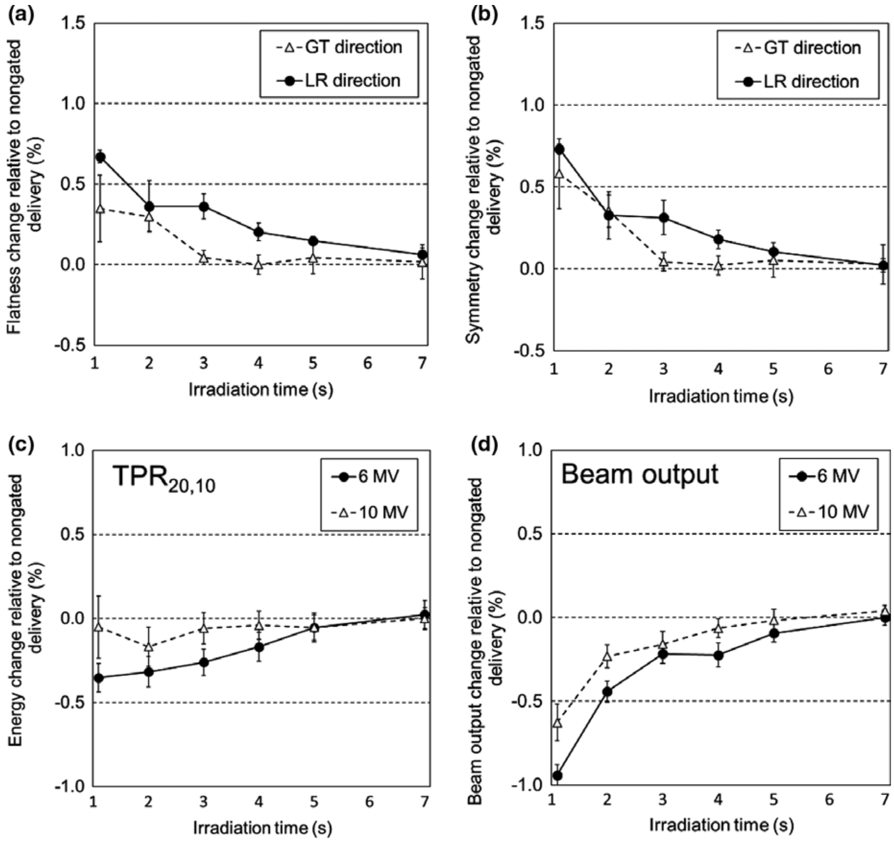

FIG. 4. Plots of differences for fixed beams in terms of (a) flatness, (b) symmetry, (c) beam quality (indicated by tissue-phantom ratio at 20- and 10-cm depths, $TPR_{20,10}$), and (d) beam output between gated and nongated beams. The differences were calculated relative to the nongated beam results using Eqs. (1)–(4). For the flatness and symmetry evaluations, measurements were performed in the gun-target (GT) and left-right (LR) directions. For the beam quality and beam output evaluation, photon energies of 6 and 10 MV were employed. Each error bar represents the standard deviation calculated from five repeated measurements. The percentage differences were below 1% for a beam-on time of 1.1–7 s. As expected, the differences were rapidly reduced when the beam-on time was extended.

TABLE II. Measured flatness and symmetry of nongated single-arc beams according to IEC 60976, under three different dose-rate conditions. The beam flatness and symmetry improved as the dose rate increased.

Dose rate (MU/min)	Flatness (%)		Symmetry (%)	
	GT	LR	GT	LR
500	105.1 ± 0.1	104.5 ± 0.0	100.9 ± 0.1	101.1 ± 0.0
250	105.3 ± 0.0	105.3 ± 0.0	101.1 ± 0.1	102.2 ± 0.1
125	105.3 ± 0.1	105.7 ± 0.1	101.2 ± 0.1	102.8 ± 0.1

GT, Gun-target direction; LR, left-right direction.

unknown to the authors. One potential explanation is provided in the Discussion section.

4. DISCUSSION

Previously, Cui et al.[4] evaluated the latency of an Elekta gating system using a Response™ interface and a C-RAD Catalyst by delivering several clinical VMAT plans. In that study, the average beam-on delay for the entire system was calculated as the difference between the actual and ideal delivery times divided by the number of gating windows, ranging from 0.1 to 0.22 s.[4] In contrast, in this study, we directly measured the latency using a multichannel storage oscilloscope. Use of this device allowed us to measure and analyze the latency in each subsystem more accurately. To the best of the authors' knowledge, this is the first report presenting these detailed latency measurement results for this subsystem. In a previous study, Noto et al.[6] reported that multiple breath-hold segmented VMAT using an Elekta Synergy® linac maintained stable and accurate dose delivery when the beam-on time between interrupts was 15 s or greater; however, in that study, no data were presented for shorter beam-on times of less than 10 s. The present study considers gated beam delivery; therefore, we evaluated the beam characteristics for shorter beam-on times of 1.1–7.0 s.

A short beam-on latency for each gated beam can increase the overall delivery time. Further, a detailed latency analysis of each subsystem may elucidate the uncertainty of gated radiotherapy and possibly improve the delivery efficiency. In this study, the latencies of the respiratory-monitoring device and the linac were measured separately, as is apparent from the data listed in Table I. Hence, it was confirmed that the major contribution to the total latency was from the linac.

As noted above, Fig. 3 shows noteworthy differences in the latencies between the first and subsequent gated beams. The smaller latencies for the subsequent gated beams were

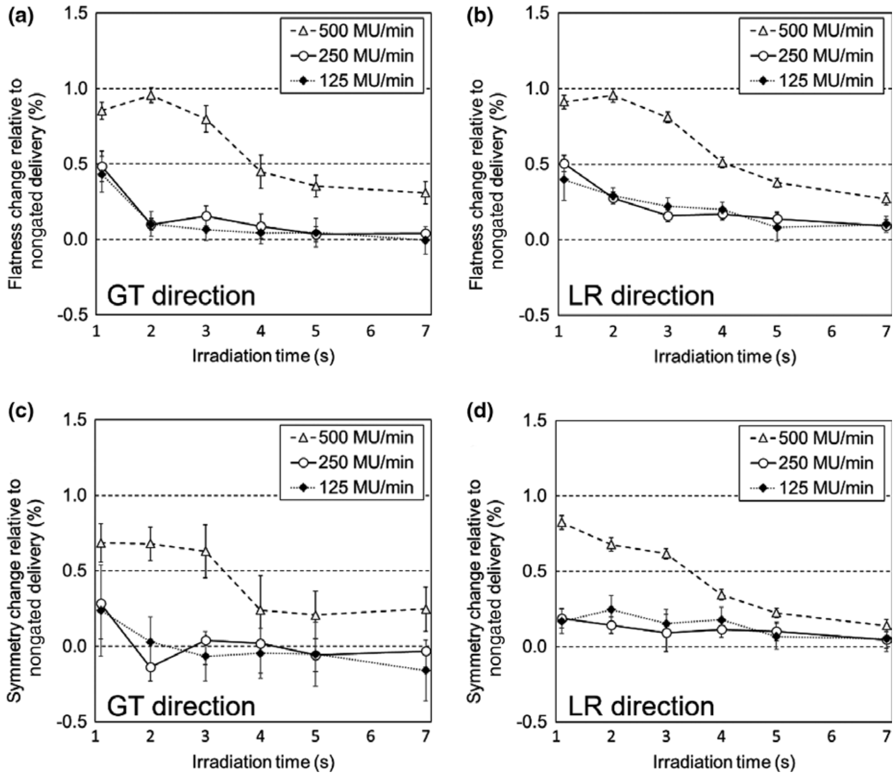

FIG. 5. Plots of differences between gated and nongated beams during 6-MV single-arc delivery under three different constant dose rates of 500, 250, and 125 MU/min, where the flatness and symmetry are shown in the (a, c, respectively) gun-target (GT) and (b, d, respectively) left-right (LR) directions. The differences were calculated relative to the nongated beam results using Eqs. (1) and (2). Each error bar represents the standard deviation calculated from five repeated measurements. The percentage differences were below 1% for a beam-on time of 1.1–7 s. Larger differences were observed for the highest dose rate of 500 MU/min.

due to the gun filament current hold-on time of 6.5 s[4]. In other words, when the beam-off time was less than 6.5 s, the gun filament temperature remained high, yielding reduced beam-on latency.

The beam-on latency was found to be larger than the beam-off latency. The larger linac beam-on latency partly results from the tuner movement required to tune the resonant frequency of the magneton. In contrast, the linac beam-off latency was considerably smaller, because it was simply obtained by interrupting the high-voltage pulses. It was also observed that the beam-on latency in the 10-MV case was considerably lower than that for the 6-MV case. A possible explanation for this difference is that the dose rate remained high for a larger range of magnetron tuner positions.

We also evaluated the gated beam characteristics for the fixed and arc beams. The flatness, symmetry, and beam quality were used to verify our new gating system, because shorter gated pulses may result in slightly lower electron energy at the accelerator exit. This is because a few hundred milliseconds may be required to maintain the magnetron resonance frequency by electromechanically moving the tuner. In addition, note that all Abches parts that may receive treatment beams are made of plastics or wood. For example, the hollow arm between the main body and each fulcrum is comprised of carbon-fiber-reinforced plastics with a wall thickness of 1 mm. As a result, we can treat patients by passing arc beams through the device. Figure 4 shows that the F and S errors of the fixed beams were within 1% for all the employed parameters, with a somewhat inferior tendency in the LR direction. This result may be explained by the fact that the beam servo was enabled in the GT direction only. Compared to the findings of a previous report,[7] more favorable agreement was obtained for the TPR $_{20,10}$ between the nongated and gated fixed beam deliveries, for both the 6- and 10-MV photon energies.

For a gated VMAT, Cui et al.[4] previously evaluated the dose distributions using gamma-index pass rates only. To date, no detailed reports have been published regarding the basic dose characteristics of Elekta-gated VMAT delivery. In this paper, we determined the beam F and S for single-arc gated beam delivery as a model of gated VMAT delivery. Although the beam F and S improved as the dose rate increased for a fixed beam (Table II), which is consistent with the findings of a previous report,[8] the differences between the nongated and gated arc beam deliveries were enhanced with increased dose rate (Fig. 5). For the fixed gated beams, larger errors for lower dose rates may arguably result from the accelerator wall temperature fluctuation, which may cause beam trajectory fluctuation. For gated arc beams, a 500-MU/min dose rate under a given delivery dose of 500 MU requires the fastest gantry rotation (1 rotation per minute), even under very frequent beam-on/off repetitions. This yields gantry backward rotation followed by gantry overrotation due to inertia. It was shown that the errors in the beam F and S remained within 1%, even under the most strict gated beam delivery conditions.

5. CONCLUSION

In this study, we evaluated the basic characteristics of an Elekta gating system. The latency of the Elekta gating system combined with an Abches device was determined using our developed measurement method and was found to be acceptable. Furthermore, we demonstrated that the beam characteristics of the gating system incorporating our respiratory indicator are comparable with nongated beams for a single-arc gated beam delivery.

CONFLICTS OF INTEREST

H.O. received research funding from Apex Medical.

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