Research Article

Accuracy of Dose Delivery in Multiple Breath-Hold Segmented Volumetric Modulated Arc Therapy: A Static Phantom Study

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Purpose. Accuracy of dose delivery in multiple breath-hold segmented volumetric modulated arc therapy (VMAT) was evaluated in comparison to noninterrupted VMAT using a static phantom. **Material and Methods.** Five VMAT plans were evaluated. A Synergy linear accelerator (Elekta AB, Stockholm, Sweden) was employed. A VMAT delivery sequence was divided into multiple segments according to each of the predefined breath-hold periods (10, 15, 20, 30, and 40 seconds). The segmented VMAT delivery was compared to noninterrupted VMAT delivery in terms of the isocenter dose and pass rates of a dose difference of 1% with a dose threshold of 10% of the maximum dose on a central coronal plane using a two-dimensional dosimeter, MatriXX Evolution (IBA Dosimetry, Schwarzenbruck, Germany). **Results.** Means of the isocenter dose differences were 0.5%, 0.2%, 0.2%, 0.0%, and 0.0% for the beam-on-times between interrupts of 10, 15, 20, 30, and 40 seconds, respectively. Means of the pass rates were 85%, 99.9%, 100%, 100%, and 100% in the same order as the above. **Conclusion.** Our static phantom study indicated that the multiple breath-hold segmented VMAT maintains stable and accurate dose delivery when the beam-on-time between interrupts is 15 seconds or greater.

1. Introduction

Although radiotherapy has been successfully applied to lung, liver, and pancreas tumors [1–3], breathing motion needs to be considered for the tumors located in proximity to the diaphragm [4–9]. A traditional approach is an enlarged internal margin that was added to a gross tumor volume (GTV) or a clinical target volume (CTV), resulting in possible higher complication to neighboring organs at risk (OARs) [10].

To minimize the internal margin, breath-hold with active breathing control (ABC) or patient voluntary breath-hold was used for intensity modulated radiation therapy (IMRT) [4, 10–12] among other techniques such as gating. IMRT provides more conformal dose for the target and more reduced dose for OARs compared to 3D conformal radiotherapy (3D-CRT). A disadvantage of IMRT is increased monitor

units and thus beam-on-time, thereby possibly causing larger intrafractional tumor localization error [13, 14].

Volumetric modulated arc therapy (VMAT) allows a faster dose delivery while gantry and multileaf collimator (MLC) are dynamically controlled [15–19]. A combination of breath-hold and VMAT may lead to a quick and accurate treatment option for a moving tumor close to diaphragm. Nevertheless, the beam-on-time for a VMAT delivery is typically two to four minutes, thereby preventing a single breath-hold treatment.

A natural solution of this problem may be a segmented breath-hold VMAT delivery having a number of breath-hold segments. However, accuracy of delivered dose in segmented breath-hold VMAT has not been reported. The purpose of this study was evaluation of delivered dose accuracy for segmented breath-hold VMAT.

TABLE 1: The monitor units per fraction, the gantry arc angles, and the beam-on-times required for noninterrupted delivery are shown for five VMAT clinical cases. When the beams were interrupted for five seconds with varied beam-on-times between interrupts, the number of VMAT segments was counted and recorded.

Case	MU/fx	Gantry arc angle (degree)	Beam-on-time (s)	Measured number of VMAT segments Beam-on-time between interrupts (s)				
				10	15	20	30	40
1	514.4	195	210	29	17	12	8	6
2	390.7	160	97	14	8	6	4	3
3	588.5	230	137	21	12	9	6	4
4	786.3	360	214	32	18	13	8	6
5	544.2	360	198	30	17	12	8	6

2. Material and Methods

2.1. Linear Accelerator and Treatment Planning System. A Synergy linear accelerator (Elekta AB, Stockholm, Sweden) with a multileaf collimator of 4 mm leaf width was used. A photon energy of 6 MV was selected. Monaco treatment planning system (Elekta AB, Stockholm, Sweden) was employed and dose calculation was performed by a built-in Monte Carlo algorithm. As a convergence criterion, a standard deviation of 3% was adopted with a dose grid size of 2 mm for this phantom study.

Five VMAT plans (three for liver and two for lung) were randomly chosen from previously delivered clinical plans, and accuracy of dose delivery in multiple breath-hold segmented VMAT was evaluated in comparison to noninterrupted VMAT. Prior to conducting the present study, dose verification for the original five VMAT plans had been performed using EDR2 films (Kodak, Rochester, USA) and a film scanner, DD system (R-Tech, Tokyo, Japan), leading to mean gamma index pass rate of 98.9% (range: 97.8 to 99.7%) under a criterion of 3 mm/3% (normalized to locally measured dose) on a central coronal plane with a dose threshold of 50% of the maximum planer dose, whereas mean isocenter dose discrepancy between the plans and the measurements was 0.5% with a range of −0.6 to 2.3%.

2.2. 2D Ionization Chamber Array System. A two-dimensional dose detector, MatriXX Evolution (IBA Dosimetry, Schwarzenbruck, Germany), was used, which had 1020 ionization microchambers distributed in an active area of $24 \times 24 \text{ cm}^2$. Each chamber had a diameter of 4.5 mm, a height of 5 mm, and a volume of 0.08 cm^3 , with chamber spacing of 7.62 mm. MatriXX was widely used for dose verification studies [20–24]. In this experiment, MatriXX was positioned at the center of a plastic water phantom, MULTICube (IBA Dosimetry, Schwarzenbruck, Germany) having a length of 31.4 cm, a width of 34 cm, and a height of 22 cm. Measurement and subsequent data analysis were performed by OmniPro-ImRT 1.5a (IBA Dosimetry, Schwarzenbruck, Germany) with a data sampling interval of 50 ms. The MatriXX needs to be calibrated for absolute dose measurement as follows. After placing the MatriXX in the MULTICube phantom, photons with energy of 6 MV and a field size of $10 \times 10 \text{ cm}^2$ were employed. Cross-calibration was performed

between each of the central four detectors of the MatriXX and an ionization chamber placed at each of the four detector positions, where a Farmer chamber (30013, PTW, Freiburg, Germany) traceable to national standards was inserted into another water equivalent phantom with a size identical to the MatriXX.

2.3. Dose Comparison of Multiple Breath-Hold VMAT Plans and Noninterrupted Plans. Five different beam-on-times between interrupts of 10, 15, 20, 30, and 40 seconds were predefined as the elapsed time from pushing the MV beam start button to pushing the MV interrupt button, which may represent typical breath-hold periods. Manually interrupted beam-off period was maintained for five seconds for all the measurements. A VMAT delivery sequence was divided into multiple segments according to each breath-hold period. The segmented VMAT delivery was compared to noninterrupted VMAT delivery in terms of the isocenter dose and the pass rates of a dose difference of 1% with a dose threshold of 10% of the maximum dose on a central coronal plane. The position of the MatriXX kept unchanged throughout this measurement. The isocenter dose was calculated by averaging doses measured by the central four chambers. Percentage difference (PD) in the isocenter dose was calculated by (1), where $\text{Dose}_{\text{segmented}}$ is an isocenter dose resulting from the segmented delivery and $\text{Dose}_{\text{original}}$ is an isocenter dose resulting from original noninterrupted delivery:

$$\text{PD} = \frac{\text{Dose}_{\text{segmented}} - \text{Dose}_{\text{original}}}{\text{Dose}_{\text{original}}} \times 100. \quad (1)$$

3. Results

Table 1 shows the monitor units per fraction, the gantry arc angles, and the beam-on-times required for noninterrupted delivery for five VMAT clinical cases. When the beams were interrupted for five seconds with varied beam-on-times between interrupts, the number of VMAT segments was counted and recorded. When the beam-on-time between interrupts was reduced to ten seconds, the number of VMAT segments was highly increased because beams were always delivered after a few seconds of preparation. Table 2 shows the mean, the SD, the minimum, and the maximum of the

TABLE 2: The mean, the SD, the minimum, and the maximum of the segmental MUs for the five cases with the five different beam-on-times between interrupts.

Beam-on-time between interrupts (s)	Case	Mean	SD	Min.	Max.
10	1	17.5	6.6	8.9	36
	2	27.9	4.6	15.7	31.1
	3	28.0	7.0	10.2	38.6
	4	24.6	10.9	12.6	55.8
	5	19.1	5.9	11.4	40.3
15	1	30.3	11.0	14.5	54.0
	2	48.8	9.3	26.9	57.6
	3	49.0	10.7	34.0	65.3
	4	43.7	16.9	25.1	83.6
	5	32.6	8.7	20.0	51.2
20	1	42.9	18.8	26.5	91.4
	2	65.1	20.5	23.9	79.0
	3	65.3	21.9	12.8	80.7
	4	60.5	25.3	25.8	112.1
	5	46.2	13.1	29.4	75.0
30	1	64.3	19.8	39.8	102.1
	2	97.7	40.5	37.4	124.3
	3	117.7	21.8	94.2	149.2
	4	98.3	38.0	63.9	171.2
	5	69.3	22.8	25.4	97.7
40	1	85.7	22.0	63.7	119.7
	2	130.2	56.3	65.4	166.3
	3	147.1	25.8	115.5	178.6
	4	131.1	53.5	75.0	220.7
	5	110.8	17.3	92.2	138.0

segmental MUs for the five different beam-on-times between interrupts.

Figure 1 depicts plots of isocenter dose differences from noninterrupted delivery for the five cases as a function of the beam-on-time between interrupts. Each circle shows each mean of the five cases, and a range is also shown as a vertical line. Means and ranges (in parentheses) among the five plans were 0.5% (0 to 1.3%), 0.2% (−0.1 to 0.6%), 0.2% (−0.2 to 0.4%), 0.0% (−0.1 to 0.2%), and 0.0% (−0.1 to 0.1%) for beam-on-times between interrupts of 10, 15, 20, 30, and 40 seconds, respectively. The average of isocenter dose differences was gradually reduced when the beam-on-time between interrupts was increased; however, the differences were not significant due to relatively large ranges in each plot.

Figure 2 shows plots of pass rates of 1% dose difference from noninterrupted delivery on a central coronal plane for the five cases as a function of the beam-on-time between interrupts. The dose difference was normalized to each local dose of noninterrupted delivery (as shown in (1)), and a dose threshold of 10% of the maximum dose on the coronal plane was employed for the pass rate calculation. Each circle shows each mean of the five cases, and a vertical line indicates

FIGURE 1: Plots of isocenter dose differences from noninterrupted delivery for the five cases as a function of beam-on-time between interrupts. Each circle shows each mean of the five cases, and a range is also shown as a vertical line.

FIGURE 2: Plots of pass rates of 1% dose difference from noninterrupted delivery on a central coronal plane for the five cases as a function of beam-on-time between interrupts. The dose difference was normalized to each local dose with no interrupt, and a dose threshold of 10% of the maximum dose on the coronal plane was employed for the pass rate calculation. Each circle shows each mean of the five cases, and a vertical line indicates a range, where most of the ranges were too small to be visualized.

a range, where most of the ranges were too small to be visualized. In detail, means and ranges (in parentheses) of the pass rates of the dose difference of 1% were 85.7 (61 to 100%), 99.9 (99.5 to 100%), 100 (100 to 100%), 100 (100 to 100%), and 100 (100 to 100%) in the same order shown in Figure 1, indicating that segmented VMAT maintains stable and accurate dose delivery when the beam-on-time between interrupts is 15 seconds or greater.

It was also confirmed that, when the beam-on-time between interrupts was 10 seconds, the worse pass rates were observed in cases 1 and 5, where the mean MUs were lower than others as shown in Table 2.

4. Discussion

Compared to step and shoot and dynamic IMRT deliveries, VMAT delivery is much quicker with decreased monitor units. However, breathing motion needs to be considered for lower-lobe lung, liver, and pancreas tumors located close to the diaphragm. Mori et al. [7] reported that the breathing amplitude for a pancreas cancer in the craniocaudal direction was approximately 10 mm. Besides, it is well known that the internal margin can be reduced under constrained breathing conditions [25–29].

The segmented breath-hold VMAT technique is regarded as a novel treatment option. The number of breath-hold segments depends on gantry speeds during delivery, total monitor units, and tolerable breath-hold periods for each patient. Dose delivery should not be less accurate when segmented VMAT is employed. This was our motivation of this study, and accuracy of the segmented breath-hold VMAT delivery was evaluated with varied beam-on-times between interrupts. The two-dimensional ion chamber array, MatriXX, employed for this study allowed measurements for absolute dose and dose distributions at the same time, facilitating an efficient quality assurance procedure even under a limited spatial resolution [21–24]. Amerio et al. [20] reported that the MatriXX resulted in good dose linearity with no dose rate dependence, and the dose discrepancy against Farmer chamber reading was less than 0.5%. In our study, the maximum isocenter dose discrepancies against original noninterrupted VMAT plans were 1.3% for a beam-on-time between interrupts of 10 seconds. The discrepancy was decreased down to 0.6% or less for the segmented beam-on-time of 15 seconds or larger. According to American Association of Physicists in Medicine (AAPM) Task Group report 53 [30], tolerance of absolute dosimetry using an ionization chamber was less than 5%. The discrepancy we obtained was much less than the AAPM recommendation, and, therefore, the segmented breath-hold VMAT delivery is regarded as sufficiently accurate.

Meanwhile, the pass rates of the dose difference on the central coronal plane were nearly 100% when the segmented beam-on-time was 15 seconds or greater. It is anticipated that the gantry inertia may require a significant transient period for gantry speed rise when the gantry restarts rotating after each beam interrupt. The dose rate may need to be adjusted during this period in order to provide accurate MU/degree specified by the treatment planning system. In our current linac controller, the dose rate changes stepwise by a factor of two, possibly leading to limited performance for the MU/degree adjustment during this transient period. When the beam-on-time between interrupts is reduced, the impact of the dose contribution during this transient period on the total dose may be increased, thereby decreasing the total dose accuracy. Based on the results obtained, it is suggested that the breath-hold time of 15 seconds or longer may be appropriate to maintain stable delivery.

The limitation of this study is that a static phantom was used for evaluating the delivery accuracy; in other words, the impact of the reproducibility of the target location on dose distributions for multiple breath-hold VMAT was not evaluated, which requires further investigation.

5. Conclusion

We have evaluated accuracy of dose delivery in multiple breath-hold segmented VMAT using a static phantom, showing that the segmented VMAT maintains stable and accurate dose delivery when the beam-on-time between interrupts is 15 seconds or greater. It is expected that the segmented breath-hold VMAT delivery technique may provide an accurate and customizable treatment option based on breathing conditions for each patient.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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