Dosimetric and delivery characterizations of full-arc and half-arc volumetric-modulated arc therapy for maxillary cancer

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We compared the efficiency and accuracy of full-arc and half-arc volumetric-modulated arc therapy (VMAT) delivery for maxillary cancer. Plans for gantry rotation angles of 360° and 180° (full-arc and half-arc VMAT) were created for six maxillary cancer cases with the Monaco treatment planning system, and delivered using an Elekta Synergy linear accelerator. Full-arc and half-arc VMAT were compared with regard to homogeneity index (HI), conformity index (CI), mean dose to normal brain, total monitor units (MU), delivery times, root mean square (r.m.s.) gantry accelerations (°/s^2), and r.m.s. gantry angle errors (°). The half-arc VMAT plans achieved comparable HI and CI to the full-arc plans. Mean doses to the normal brain and brainstem with the half-arc VMAT plans were on average 16% and 17% lower than those with the full-arc VMAT plans. For other organs at risk (OARs), no significant DVH differences were observed between plans. Half-arc VMAT resulted in 11% less total MU and 20% shorter delivery time than the full-arc VMAT, while r.m.s. gantry acceleration and r.m.s. gantry angle error during half-arc VMAT delivery were 30% and 23% less than those during full-arc VMAT delivery, respectively. Furthermore, the half-arc VMAT plans were comparable with the full-arc plans regarding dose homogeneity and conformity in maxillary cancer, and provided a statistical decrease in mean dose to OAR, total MU, delivery time and gantry angle error. Half-arc VMAT plans may be a suitable treatment option in radiotherapy for maxillary cancer.

Keywords: Volumetric-modulated arc therapy; gantry acceleration; gantry angle error; planning study; maxillary cancer

INTRODUCTION

Volumetric-modulated arc therapy (VMAT) has been characterized as intensity-modulated radiotherapy (IMRT) in a single gantry arc, in which gantry speed, dose rate and leaf speed of the multileaf collimator (MLC) are varied during gantry rotation [1]. VMAT significantly improves delivery efficiency while maintaining similar treatment plan quality to IMRT [2].

In contrast, 180° partial-arc VMAT has been employed for lung cancer treatment to reduce doses in contralateral healthy organs [3]. Dosimetric and delivery efficiency comparisons between 360° single-arc and 180–200° partial-arc VMAT for lung cancer have been made, reporting that partial-arc VMAT significantly reduced mean dose to the contralateral lung with decreased delivery time [4]. To our

knowledge, however, no further comparisons of full-arc and half-arc VMAT for tumors other than lung cancer have been reported. We speculated that a regular-shaped peripheral cancer such as a maxillary cancer may benefit from half-arc VMAT due to its location.

The purpose of this paper is comparison of dosimetric and delivery characterizations between full-arc and half-arc VMAT for maxillary cancer. Delivery was characterized by recording gantry angle error and gantry acceleration during VMAT delivery in a log file.

MATERIALS AND METHODS

Six patients with localized maxillary cancer were enrolled. The patients were helically scanned on an Aquilion LB (Toshiba, Ootawara, Japan) computer tomography unit with

a gantry rotation time of 0.5 s and the images were reconstructed with a slice thickness of 2 mm. Gross tumor volume (GTV) was defined as a visible tumor at the head window settings. Clinical target volume (CTV) was defined by adding an isotropic margin of 5 mm to the GTV. Planning target volume (PTV) was further defined by adding an isotropic margin of 5 mm to the CTV to account for setup un-

certainty and mechanical inaccuracy. The normal brain, brainstem, spinal cord, optic chiasm, ipsilateral and contralateral eyes, and ipsilateral and contralateral optic nerves were contoured as organs at risk (OARs). The tumor sizes and positions for the six cases are shown in Table 1.

VMAT plans were created using the Monaco 3.0 (Elekta, Maryland Heights, Missouri, USA) treatment planning

Table 1. Tumor sizes, positions and gantry angle ranges used for half-arc VMAT deliveries

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
PTV (cm^3)	280.1	129.8	347.9	239.7	302.8	217.5
CTV (cm^3)	181.2	76	245.1	150.7	199.3	129.4
GTV (cm^3)	100.8	32.2	142.2	80.5	112.6	62.8
Lesion position	R	L	R	L	L	L
Gantry angle range (°)	225–45	300–120	225–45	315–135	315–135	315–135

R: right side, L: left side.
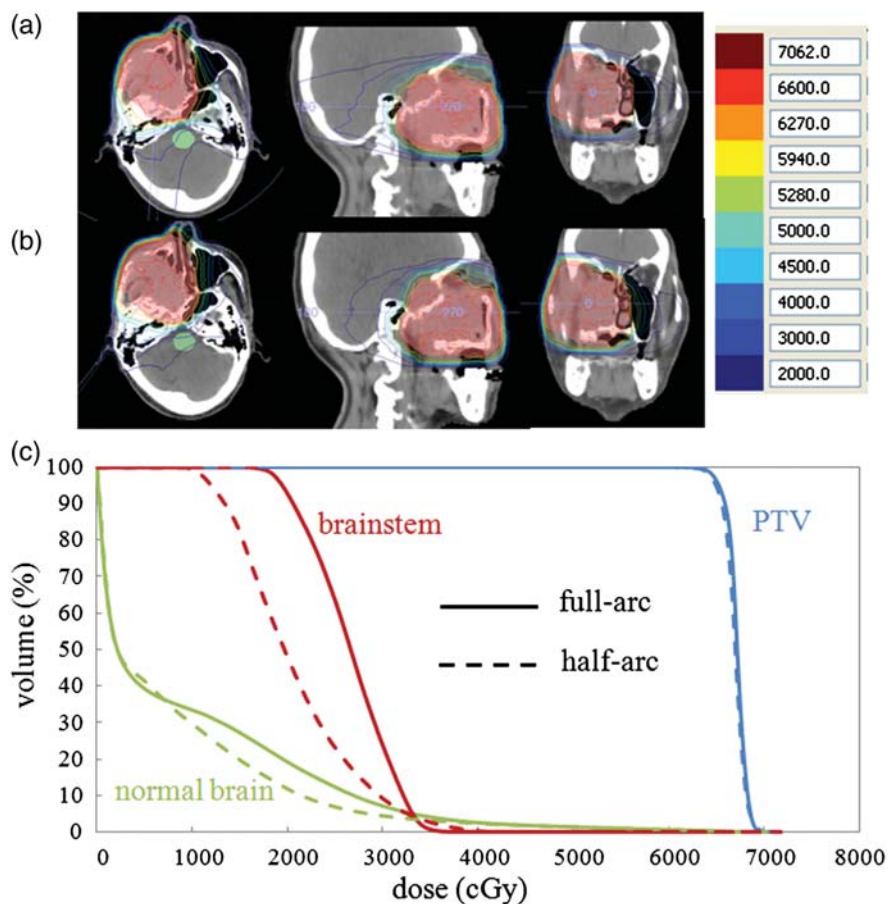

Figure 1. Dose distributions calculated by (**a**) full-arc and (**b**) half-arc VMAT planning for a patient with maxillary cancer; (**c**) comparison of dose volume histograms (DVHs) between full-arc (solid line) and half-arc (dashed line) VMAT plans for the same patient   The PTV is shown as a translucent pink region. Compared with the full-arc plan, the half-arc plan provided substantially lower doses to the normal brain and brainstem while maintaining a nearly identical DVH for the PTV.

Table 2. Dosimetric comparisons between full-arc and half-arc VMAT plans

	Full-arc	Half-arc	(n = 6) P value
PTV			
HI			0.075
Mean	0.19	0.21	
Range	0.14–0.32	0.15–0.31	
$CI_{95\%}$			0.345
Mean	1.1	1.1	
Range	0.9–1.2	1.0–1.2	
$CI_{80\%}$			0.249
Mean	1.6	1.6	
Range	1.4–1.8	1.4–1.9	
$CI_{50\%}$			0.028
Mean	2.8	2.6	
Range	2.5–3.4	2.3–3.2	
Normal brain D_{mean} (cGy)			0.028
Mean	918.7	768.3	
Range	405.5–1623.2	346.8–1335.0	
Brainstem D_{mean} (cGy)			0.028
Mean	2344.7	1943.8	
Range	1805.9–2655.6	1403.1–2273.2	
Spinal cord D_{mean} (cGy)			0.080
Mean	1129.8	890	
Range	161.6–2341.9	164.0–1709.5	
Optic chiasm D_{mean} (cGy)			0.463
Mean	2226.2	2117.5	
Range	568.7–3224.3	615.4–3344.8	
Ipsilateral eye D_{mean} (cGy)			0.280
Mean	3442.6	3254.3	
Range	1487.4–5157.2	1338.4–4943.6	
Ipsilateral optic nerve D_{mean} (cGy)			0.600
Mean	4256.5	4212.3	
Range	2548.4–6088.7	2274.6–6134.2	
Contralateral eye D_{mean} (cGy)			0.753
Mean	989.5	1006	
Range	712.1–1512.8	769.3–1542.0	

Continued

Table 2. *Continued*

	Full-arc	Half-arc	(n = 6) P value
Contralateral optic nerve D_{mean} (cGy)			0.345
Mean	2843.6	2724	
Range	1572.7–3454.3	1721.2–3378.1	

The Wilcoxon signed-rank test resulted in a statistically significant mean dose reduction to the normal brain and brainstem in the half-arc VMAT plans ($P < 0.05$). HI, homogeneity index; CI, conformity index.

system (TPS) with gantry rotation angles of 360° (full-arc VMAT) and 180° (half-arc VMAT). Gantry angle ranges used for the half-arc VMAT deliveries are shown in Table 1. The collimator and couch angles were fixed at 0°. A dose of 66 Gy in 33 fractions was prescribed to 95% of the PTV, and maximum dose was restricted to 110% of the prescribed dose. Dose constraints for OARs were given as follows: brainstem max dose ≤50 Gy, spinal cord max dose ≤45 Gy, optic chiasm mean dose, contralateral eye max dose and contralateral optic nerve mean dose ≤45 Gy. Ipsilateral eye and optic nerve maximum dose were minimized while maintaining the target D95 prescription. The Monaco TPS provides Monte Carlo dose calculations with a grid size of 3 mm and variance of 3%.

Dosimetric comparisons between the full- and half-arc VMAT were performed with identical isocenter positions and dose constraints. For the PTV, a homogeneity index (HI) was calculated using the following formula [5]:

$$HI = \frac{D_{2\%} - D_{98\%}}{D_{50\%}} \quad (1)$$

Where $D_{2\%}$, $D_{98\%}$ and $D_{50\%}$ are doses that cover 2%, 98% and 50% of the PTV, respectively. A conformity index (CI) was calculated using the following formula [6]:

$$CI = \frac{VRI}{TV} \quad (2)$$

Where VRI was the volume of the reference isodose and TV was the target volume. $CI_{95\%}$, $CI_{80\%}$ and $CI_{50\%}$ were calculated, for which the reference isodose percentages were 95%, 80% and 50%, respectively. With regard to OAR, the mean dose to each OAR was calculated.

A 6-MV photon beam with an MLC leaf width of 10 mm was used for VMAT delivery using the Synergy linear accelerator (Elekta, Crawley, UK). Treatment plans were transferred from the TPS to a Desktop Pro 7.01 linac controller via a Mosaiq v1.6 (Elekta, Sunnyvale, California, USA) record and verify system. Total monitor units (MU), mean dose rate, delivery time, gantry angle error and gantry

acceleration were evaluated using a log file that recorded cumulative MU as well as planned and actual gantry angles every 250 ms. The gantry angle error was calculated by subtracting the planned gantry angle from the actual gantry angle for each treatment time. Data were analyzed using the Wilcoxon signed-rank test with statistical significance set at $P < 0.05$. Statistical analysis was performed with SPSS v.19.0 (IBM, Chicago, IL, USA).

RESULTS

Figure 1 shows representative dose distributions and dose volume histograms of full-arc and half-arc VMAT for the same patient. Compared with the full-arc VMAT plan, the half-arc plan provided substantially lower doses to the normal brain and brainstem while maintaining a nearly identical DVH for the PTV.

Table 2 compares the HI of the PTV, CI and mean doses to the OAR between the full- and half-arc VMAT plans, with data shown as group averages with ranges ($n = 6$). The HI, $CI_{95\%}$, $CI_{80\%}$, the mean doses to the spinal cord, optic chiasm, ipsilateral and contralateral eyes, and ipsilateral and contralateral optic nerves did not significantly differ

between the full- and half-arc VMAT plans ($P > 0.05$). In contrast, mean doses to the normal brain and brainstem in the half-arc VMAT plans were on average 16% and 17% lower than those in the full-arc plans, with these differences being statistically significant ($P < 0.05$).

Figure 2 shows plots of gantry acceleration and gantry angle errors as a function of treatment time during full- and half-arc VMAT deliveries for a patient study set. Full-arc VMAT led to a larger gantry acceleration and larger gantry angle error than the half-arc VMAT. In addition, gantry acceleration and gantry angle error appeared to show a considerable correlation.

Figure 3a shows plots of root mean square (r.m.s.) gantry angle errors as a function of the r.m.s. gantry acceleration, whereas Figure 3b shows plots of r.m.s. gantry acceleration as a function of arc angle divided by total MU during each of the full-arc and half-arc VMAT deliveries. The r.m.s. gantry angle errors were linearly related to r.m.s. gantry acceleration with a coefficient of determination (R^2) of 0.72. The r.m.s. gantry angle acceleration was linearly related to arc angle divided by total MU with an R^2 value of 0.69.

Table 3 compares total MU, mean dose rate, delivery time, r.m.s. gantry acceleration and r.m.s. gantry angle error
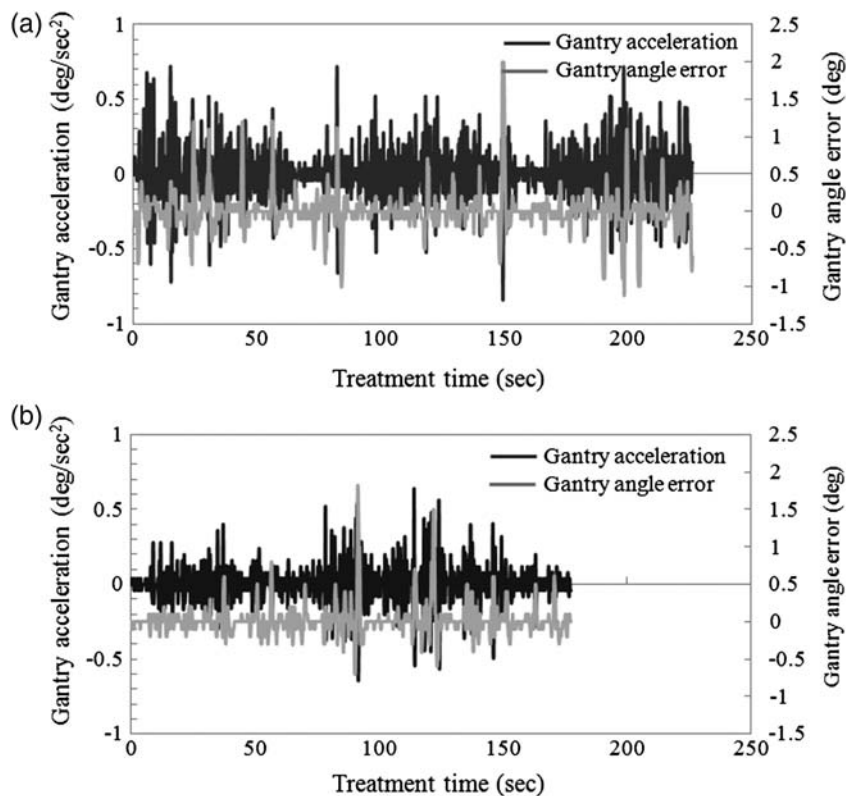

Figure 2. Plots of gantry acceleration (black line) and gantry angle errors (gray line) as a function of treatment time for a patient study set, with (**a**) full-arc and (**b**) half-arc VMAT. On average, the full-arc VMAT led to larger gantry acceleration and a larger gantry angle error than the half-arc VMAT. Gantry acceleration and gantry angle error appeared to show a slight correlation.
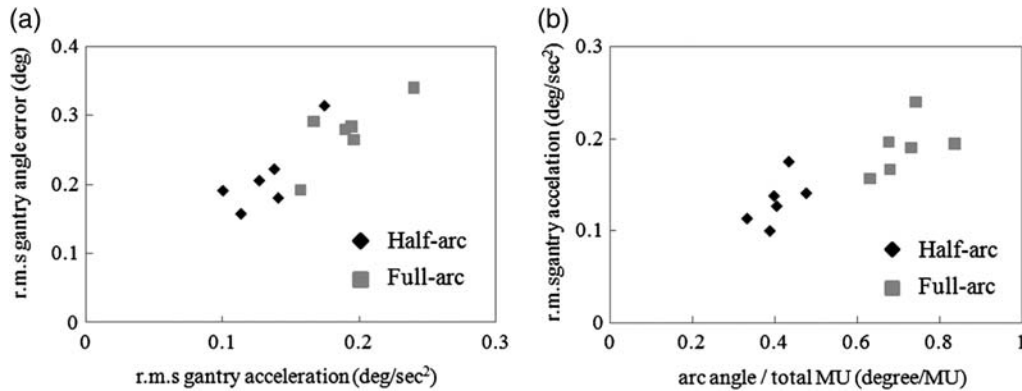
Figure 3. Relationship between full-arc (gray square) and half-arc (black diamond) VMAT deliveries. (**a**) r.m.s. gantry angle error as a function of r.m.s. gantry acceleration during each delivery ($n = 6$), and (**b**) r.m.s. gantry acceleration as a function of arc angle divided by total MU for each delivery.

between the half-arc and full-arc VMAT plans. On average, the half-arc plans resulted in 11% less total MU, 20% shorter delivery time, 12% higher mean dose rate, 30% less r.m.s. gantry acceleration and 23% less r.m.s. gantry angle error than the full-arc plans. Differences in all parameters were statistically significant according to the Wilcoxon signed-rank test ($P < 0.05$).

DISCUSSION

In this study, we demonstrated that half-arc VMAT plans provided significantly reduced doses to the normal brain and brainstem compared with full-arc VMAT plans, while maintaining nearly identical dose homogeneity and conformity in the PTV. For other OARs, no significant DVH differences were observed between the full-arc and half-arc VMAT plans, possibly because these OARs were located closer to the PTV. These results suggest that half-arc VMAT planning provides a clinical advantage in maxillary cancer. In contrast, conventional 3D plans for a maxillary cancer resulted in much higher doses to OARs, whereas four- and nine-field IMRT plans provided target coverage and sparing ability similar to our half-arc plans [7]. Our half-arc VMAT plan may provide a better treatment option due to significantly decreased delivery time compared with the IMRT and 3D plans. The dosimetric findings in the present study were consistent with those in a previous report in patients with lung cancer [4].

We confirmed that the delivery time and total MU required for half-arc VMAT delivery for maxillary cancer were less than those for full-arc delivery. This reduced delivery time also likely improves patient comfort and reduces intrafractional movement. The reduced MU may decrease the risk of secondary cancer [8].

With regard to gantry acceleration and gantry angle error during VMAT delivery, plots of r.m.s. gantry angle error

Table 3. Comparison of delivery parameters between full-arc and half-arc VMAT plans

	Full-arc	Half-arc	(*n* = 6) *P* value
Total MU			0.028
Mean	506.2	449.2	
Range	430.0–570.0	378.0–541.0	
Mean dose rate (MU/min)			0.046
Mean	135.6	152.7	
Range	116.7–164.3	135.0–175.9	
Delivery time (s)			0.028
Mean	223.2	178.3	
Range	179.0–264.0	143.0–210.0	
r.m.s. gantry acceleration ($°/s^2$)			0.028
Mean	0.19	0.13	
Range	0.16–0.24	0.10–0.18	
r.m.s. gantry angle error ($°$)			0.028
Mean	0.28	0.21	
Range	0.19–0.34	0.16–0.31	

Group averages with ranges in parentheses are shown ($n = 6$). The Wilcoxon signed-rank test resulted in statistically significant differences ($P < 0.05$) for all parameters shown below.

versus r.m.s. gantry acceleration during the half-arc and full-arc VMAT deliveries showed an approximately linear correlation. The greater gantry angle acceleration during full-arc delivery may be due to increased arc angle per total MU. Furthermore, r.m.s. values in half-arc deliveries were

smaller than those in the full-arc deliveries. This finding might suggest that larger acceleration of the gantry and the accompanying greater inertia might result in a larger gantry angle error.

CONCLUSION

We have demonstrated that half-arc VMAT has clinical advantages over full-arc VMAT for maxillary cancer. Advantages of the half-arc VMAT planning include improved OAR sparing with nearly identical HI and CI for the PTV. The advantages of the half-arc VMAT delivery include reductions in total MU and delivery time, thereby leading to better patient comfort and treatment throughput. Gantry angle error was also reduced during half-arc VMAT delivery.

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