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FULL PAPER

Non-coplanar VMAT plans for lung SABR to reduce dose to the heart: a planning study

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Objective: This study aimed to compare the plan quality of non-coplanar partial arc (NPA) volumetric modulated arc therapy (VMAT) to that of coplanar partial arc (CPA) VMAT for stereotactic ablative radiotherapy (SABR) for lung cancer.

Methods: A total of 20 patients treated for lung cancer with the SABR VMAT technique and whose lung tumors were close to the heart were retrospectively selected for this study. For the CPA VMAT, three coplanar half arcs were used while two coplanar half arcs and one non-coplanar arc rotating 315°–45° with couch rotations of 315° ± 5° were used for the NPA VMAT. For each patient, identical CT image sets and identical structures were used for both the CPA and NPA VMAT plans. Dose–volumetric parameters of each plan were analyzed.

Results: For the planning target volume and both lungs, no statistically significant differences between the CPA

and NPA VMAT plans were observed in general. For the heart, average values of $D_{0.1cc}$ of the CPA and NPA VMAT plans were 29.42 ± 13.37 and 21.71 ± 9.20 Gy, respectively ($p < 0.001$). For whole body, the mean dose and the gradient index of the CPA VMAT plans were 1.2 ± 0.5 Gy and 4.356 ± 0.608 while those of the NPA VMAT plans were 1.1 ± 0.5 Gy and 4.111 ± 0.480 , respectively (both with $p < 0.001$).

Conclusion: The NPA VMAT proposed in this study showed more favorable plan quality than the CPA VMAT plans for lung SABR with tumors located close to the heart.

Advances in knowledge: For lung SABR, NPA VMAT can reduce doses to the heart as well as whole-body irradiation.

INTRODUCTION

Stereotactic ablative radiotherapy (SABR) has become an established treatment option for inoperable early stage non-small cell lung cancer as well as lung metastases, showing favorable clinical data.^{1,2} To achieve high local control rate and low toxicity of lung SABR, various treatment planning techniques utilizing non-coplanar beams were proposed and investigated to acquire an optimal dose distributions.^{3–7}

Dong et al proposed 4 π non-coplanar plans to reduce doses to organs at risk (OARs), while improving planning target

volume (PTV) coverage for centrally located or large lung tumors.³ They showed superior plan quality to that of volumetric modulated arc therapy (VMAT) with two full arcs. Although optimal dose distributions could be acquired by 4 π non-coplanar plans, the treatment delivery times were long since more than 10 non-coplanar beams should be utilized to acquire an optimal dose distribution. Moreover, since various non-coplanar beams were used, the treatment delivery procedure was complex. In addition, there was a potential problem of collision between the gantry head and patient body. Despite of the improved dose distributions, 4 π

non-coplanar plans could not be widely adopted in the clinical setting owing to issues of practicability. Fitzgerald et al compared three types of VMAT plans for lung SABR, which were coplanar full arc (CFA), coplanar partial arc (CPA), and non-coplanar partial arc (NPA) VMAT plans.⁴ They demonstrated that the NPA plans improved conformity of the PTVs while reducing irradiation of body by intermediate doses as well as the maximum doses to spinal cord. In that study, the locations of the target volumes were various in both lungs and the number of cases analyzed in that study was limited (10 cases); therefore, a deep analysis on the benefit of the NPA plans could not be performed. Ishii et al investigated the NPA VMAT plans for lung SABR specifically focusing on the centrally located lung tumors.⁶ They reported that the NPA VMAT plans could reduce maximum doses to contralateral lung, esophagus, spinal cord, aorta, and vena cava compared to those of CPA VMAT plans; however, the absolute differences in those maximum doses to those OARs between NPA and CPA VMAT plans were minimal. For the whole lungs, the average volume irradiated by at least 10 Gy (V_{10Gy}) of the NPA VMAT plans was larger than that of the CPA VMAT plans. In that study, the couch rotation angle of the NPA was only $\pm 15^\circ$. On the other hand, Fleckenstein et al demonstrated the reduced V_{10Gy} of the NPA VMAT plans compared to CPA VMAT plans for the lung tumors located in the peripheral regions in the lungs.⁵ Moreover, the median doses to the gross tumor volumes (GTVs) increased for the NPA VMAT plans when delivering non-uniform doses to the PTV. In this case, the couch rotation angles of the NPAs were 0° , $\pm 35^\circ$, and 90° (four couch angles). Yu et al demonstrated chest wall dose reduction using the NPA VMAT with a couch rotation angle of 15° for lung SABR with tumors located close to the chest wall compared to the CPA VMAT.⁷

Various studies were performed on the NPA VMAT plans for lung SABR and comprehensively reviewing the results of the previous studies, the NPA VMAT might be selectively beneficial for lung SABR with tumors at specific locations in the lung when combining particular gantry rotations and couch angles appropriately.³⁻⁷ For example, lung SABR with tumors located close to heart might take advantage of NPA VMAT plans, which is a challenging case to deliver a prescription dose to the target volume while keeping doses to heart less than the tolerance level because of the proximity of the heart to the target volume.⁸ However, to the best of our knowledge, no study has investigated this yet. Therefore, we investigated the quality of the NPA VMAT plans compared to the CPA VMAT plans by utilizing 20 patients who received lung SABR with tumors located close to the heart.

METHODS AND MATERIALS

Patient selection and simulation

After an approval from the institutional review board, a total of 20 patients treated for lung cancer with SABR VMAT technique and whose lung tumors were close to the heart were retrospectively selected for this study (IRB No. 1903-145-1020). For the selected patients, the shortest distance from the centroid of the target volume to the surface of the heart was 2.8 ± 1.2 cm on average. To apply anterior NPA beams, only patients with lung tumors not concealed by the heart from the anterior view were selected. For all the patients selected for this study, tumors were located in the

left lung. All patients were scanned using the Brilliance CT Big BoreTM (Phillips, Cleveland, OH). For each patient, 10 pPhase four-dimensional CT images were acquired using the Real-time Position ManagementTM (RPM, Varian Medical Systems, Palo Alto, CA) system to define the internal target volume (ITV) for VMAT planning. The slice thickness of the CT images was 2 mm. When acquiring the CT images, all patients were immobilized using the Body Pro-LokTM (CIVICO, Orange City, IA) system to reduce the respiratory motion of the lung tumors for reduction of the ITV size.

Treatment planning

The PTV was defined by adding an isotropic margin of 5 mm from the ITV in the 80% phase CT image set.⁹ The prescription dose to the PTV was 60 Gy in 4 fractions for all patients, except for three patients whose PTVs were extremely close to the heart (patient no. 9, 11, and 16). For those three patients, prescription doses were reduced to keep the doses to the heart less than the tolerance level of the heart in accordance with the National Comprehensive Cancer Network Clinical Practice Guidelines in Oncology (NCCN Guidelines[®], National Comprehensive Cancer Network, Fort Washington, PA). The prescription doses of two patients (Patient no. 9 and 11) were 48 Gy in 4 fractions, and that of the other patient (Patient no. 16) was 54 Gy in 4 fractions. VMAT plans were generated using a 6 MV flattening filter free (FFF) beam of the TrueBeam STx with the High-Definition 120TM multileaf collimator (MLC) (Varian Medical Systems, Palo Alto, CA). For both the CPA and NPA VMAT planning, the EclipseTM system (Varian Medical Systems, Palo Alto, CA) was used. For the CPA VMAT plans, three coplanar half arcs rotating near the ipsilateral lung were used to minimize the doses to the contralateral lung (one arc was rotated from 180° to 0° , whereas the other two half arcs were rotated from 0° to 180°).¹⁰ For the NPA VMAT plans, two coplanar half arcs (one arc was rotated from 180° to 0° , whereas the other half arc was rotated from 0° to 180°) and one non-coplanar quarter arc rotating 315° to 45° with a couch rotation of $315^\circ \pm 5^\circ$ were used. The couch angle was chosen to minimize the irradiation of the heart in the beam's eye view (BEV). The arc configurations of the CPA and NPA VMAT plans are shown in Figure 1. The procedure to determine the optimal couch angle in this study is shown in Figure 2. Therefore, a total of 540° and 450° rotations of the gantry were used for the generation of CPA and NPA VMAT plans in this study, respectively. For both, the CPA and NPA VMAT plans were optimized using the progressive resolution optimizer (PRO3, v. 13, Varian Medical Systems, Palo Alto, CA). The dose-volume constraints during optimization were set according to the NCCN Guidelines. For every VMAT plan, the jaw tracking technique was applied. After optimization, the dose distributions were calculated using the anisotropic analytic algorithm (AAA, v. 13, Varian Medical Systems, Palo Alto, CA) with a dose calculation grid size of 1 mm.¹¹ For both, the CPA and NPA VMAT plans were normalized to cover 95% of the PTV volume with 100% of the prescription dose.

Evaluation of the treatment plans

For each plan, the total monitor units (MU) were acquired. For the PTVs, the maximum, mean, and minimum doses of the

Figure 1. For the CPA VMAT plans (a), three coplanar half arcs rotating near the ipsilateral lung were used to minimize the doses to the contralateral lung (one arc was rotated from 180° to 0°, whereas the other two half arcs were rotated from 0° to 180°). For the NPA VMAT plans (b), two coplanar half arcs (one arc was rotated from 180° to 0°, whereas the other half arc was rotated from 0° to 180°) and one non-coplanar quarter arc rotating 315° to 45° with a couch rotation of 315° ± 5° were used. The couch angle was chosen to minimize the irradiation of the heart in the beam's eye view. CPA, coplanar partial arc; NPA, non-coplanar partial arc; VMAT, volumetric modulated arc therapy.

PTV were calculated. In addition, the minimum doses to 98% vol of the PTV ($D_{98\%}$), $D_{95\%}$, $D_{5\%}$, and $D_{2\%}$ were calculated. The conformity index (CI) and the homogeneity index (HI) for each PTV were calculated as follows.^{12,13}

$$\text{Conformity index (CI)} = \frac{V_{\text{reference isodose}}}{\text{Volume of the target volume}} \quad (1)$$

$$\text{Homogeneity index (HI)} = \frac{D_{5\%} - D_{95\%}}{\text{mean dose}} \quad (2)$$

Here, the reference isodose was the prescription dose.

For both the right (contralateral) and left (ipsilateral) lungs, the mean dose, $D_{1500\text{cc}}$, $D_{1000\text{cc}}$, $V_{20\text{Gy}}$, $V_{10\text{Gy}}$, and $V_{5\text{Gy}}$ were

Figure 2. A procedure to determine the optimal NPA is shown. From the beam's eye view, the NPA with a couch angle of 315° is examined at the gantry angles from 315° to 45° at intervals of 15° (from (a) to (f)). The couch angle is adjusted within ±5° from the original value of 315° to minimize the overlap between the target volume and the heart. NPA, non-coplanar partial arc.

calculated. Those dose–volumetric parameters were also calculated for the whole lungs. For the heart, the maximum dose, mean dose, $D_{0.1\text{cc}}$, $D_{2\%}$, $V_{34\text{Gy}}$, and $V_{28\text{Gy}}$ were calculated. For the esophagus, the mean dose, $V_{30\text{Gy}}$, and $V_{18.8\text{Gy}}$ were calculated. For the trachea and bronchi, the values of $D_{2\%}$, $D_{0.1\text{cc}}$, $V_{34.8\text{Gy}}$, and $V_{15.6\text{Gy}}$ were calculated. For the spinal cord, the maximum dose, $D_{0.1\text{cc}}$, $D_{2\%}$, $V_{26\text{Gy}}$, and $V_{20.8\text{Gy}}$ were calculated. For skin, $D_{0.1\text{cc}}$, $D_{2\%}$, $V_{36\text{Gy}}$, and $V_{33.2\text{Gy}}$ were calculated. For the stomach, $V_{27.2\text{Gy}}$ and $V_{17.6\text{Gy}}$ were calculated.

For the whole body of a patient, mean dose to whole body as well as $V_{10\%}$, $V_{30\%}$, $V_{50\%}$, $V_{70\%}$, and $V_{90\%}$ of the whole body were acquired. The gradient index (GI) proposed by Paddick and Lippitz was calculated as follows.¹⁴

$$\text{Gradient index (GI)} = \frac{V_{50\% \text{ of the body}}}{V_{100\% \text{ of the body}}} \quad (3)$$

To examine the statistical significances of the differences in the parameters between the CPA and the NPA VMAT plans, a paired *t*-test was performed. In this study, *p* values of less than 0.05 were regarded as statistically significant.

RESULTS

Total monitor unit and dose–volumetric parameters of the planning target volume

The average total MU of CPA and NPA VMAT plans were 3673 ± 315 and 3723 ± 494 MU, respectively (*p* = 0.419).

The dose distributions of the CPA and NPA VMAT plans of the representative patients are shown in Figure 3. One patient is a representative case with the original prescription dose of 60 Gy, while the other patient is a representative case with a prescription dose of 48 Gy that was reduced from the original prescription dose of 60 Gy to keep the delivered dose to the heart being less than the tolerance level. The dose–volume histograms (DVHs) of those representative patients are shown in Figure 4.

The dose–volumetric parameters of the PTVs from both the CPA and NPA VMAT plans are shown in Table 1. In general, the dose–volumetric parameters of the PTV of CPA VMAT plans were higher than those of NPA VMAT plans; however, all of them showed no statistically significant differences except the minimum dose. The PTV minimum dose of CPA VMAT plans was higher than that of NPA VMAT plans by 0.66 Gy on average (*p* = 0.043). The values of $D_{95\%}$ of CPA VMAT plans were identical to those of NPA VMAT plans because all the plans were normalized to cover 95% vol of the PTV with 100% of the prescription dose. The values of CI and HI indicated a more favorable plan quality of the NPA VMAT plans than the CPA VMAT plans; however, those differences were minimal and not statistically significant (1.001 vs 1.008 for CI with *p* = 0.226 and 0.072 vs 0.075 for HI with *p* = 0.518).

Dose–volumetric parameters of the lungs

The dose–volumetric parameters of lungs are shown in Table 2. For the right lung (contralateral lung), the mean dose, $D_{1500\text{cc}}$, $D_{1000\text{cc}}$, and $V_{5\text{Gy}}$ of CPA VMAT plans were higher than those of NPA VMAT plans on average with statistical significance (all

Figure 3. One patient (Patient no. 6) is a representative case with the original prescription dose of 60 Gy (a), while the other patient (Patient no. 9) is a representative case with a prescription dose of 48 Gy that was reduced from the original prescription dose of 60 Gy to keep the delivered dose to the heart less than the tolerance level (b). The dose distributions of the NPA (a) and CPA VMAT plans (b) of the Patient no. 6 are shown. Those of the NPA (c) and CPA VMAT plans (d) of the Patient no. 9 are also shown. CPA, coplanar partial arc; NPA, non-coplanar partial arc; VMAT, volumetric modulated arc therapy.

with $p < 0.006$). Especially, the V_{5Gy} of the contralateral lung of the NPA VMAT plans was much smaller than that of the CPA VMAT plans (29.21 cm^3 for the CPA VMAT plans vs 8.12 cm^3 for the NPA VMAT plans with $p = 0.002$). On the contrary, for the left lung (ipsilateral lung) the mean dose and V_{5Gy} of CPA VMAT plans were lower than those of NPA VMAT plans on average with statistical significance (all with $p < 0.002$). For both lungs, no dose–volumetric parameters examined in this study showed statistically significant differences (all with $p > 0.05$).

Dose–volumetric parameters of organs at risk other than lungs

The dose–volumetric parameters of various OARs other than lungs are shown in Table 3. For the heart, every dose–volumetric parameter of CPA VMAT plans was higher than those of NPA VMAT plans on average with statistical significance (all with $p < 0.05$). The maximum dose and $D_{0.1cc}$ of CPA VMAT plans were 32.40 and 29.42 Gy, respectively, while those of NPA VMAT plans were 25.72 and 21.71 Gy, respectively (both with $p < 0.001$). The mean doses to the heart of CPA and NPA VMAT plans were 2.85 and 2.34 Gy, respectively ($p < 0.001$). In the cases of the

Figure 4. One patient (Patient no. 6) is a representative case with the original prescription dose of 60 Gy, while the other patient (Patient no. 9) is a representative case with a prescription dose of 48 Gy that was reduced from the original prescription dose of 60 Gy to keep the delivered dose to the heart less than the tolerance level. The DVHs of the PTV and lungs of the Patient no. 6 (a) and no. 9 (c) are shown. The DVHs of the other OARs of the Patient no. 6 (b) and no. 9 (d) are also shown. CPA, coplanar partial arc; DVH, dose–volume histogram; NPA, non-coplanar partial arc; OARs, organs at risk; PTV, planning target volume.

three patients with prescription doses of 48 and 54 Gy due to the extreme proximity of the PTVs to the heart, the values of $D_{0.1cc}$ were less than the tolerance level of 34 Gy in the NPA VMAT plans while those of the CPA VMAT plans were higher than 34 Gy ($D_{0.1cc}$ of the heart for patients no. 9, 11, and 16 were 43.84, 52.31, and 56.25 Gy, respectively). Besides those 3 patients, 5 patients from 17 patients with a prescription dose of 60 Gy showed higher values of $D_{0.1cc}$ of the heart than 34 Gy in the CPA VMAT plans (ranging from 34.15 to 46.75 Gy), while no patients showed higher values of $D_{0.1cc}$ than 34 Gy in the NPA VMAT plans. The volumes of the heart irradiated by relatively low doses (20 and 10 Gy) in the CPA VMAT plans were 31.04 and 143.01 cm^3 , respectively, while those in the NPA VMAT plans were 24.32 and 110.68 cm^3 , respectively (both with $p < 0.001$).

Dose–volumetric parameters of the whole body

The dose–volumetric parameters of the whole body are shown in Table 4. The mean dose, $V_{10\%}$, $V_{30\%}$, $V_{50\%}$, $V_{70\%}$, and the GI consistently indicated that the irradiation of normal tissue of CPA VMAT plans was higher than that of NPA VMAT plans with statistical significance (all with $p < 0.03$). The value of $V_{90\%}$ also indicated that the normal tissue irradiation of CPA VMAT plans was higher than that of NPA VMAT plans, however, that difference was not statistically significant ($p > 0.05$).

DISCUSSION

In the present study, the NPA VMAT plans showed more favorable plan quality than the CPA VMAT plans for the challenging cases of lung SABR with tumors located close to the heart. The dose–volumetric parameters of every OAR of all the CPA VMAT

Table 1. Dose–volumetric parameters of the PTV

DV parameter	Coplanar VMAT	Non-coplanar VMAT	<i>p</i>
Maximum dose (Gy)	62.86 ± 2.66	62.78 ± 3.39	0.739
Mean dose (Gy)	60.28 ± 2.92	60.15 ± 3.42	0.524
Minimum dose (Gy)	51.03 ± 10.76	50.37 ± 11.18	0.043
D _{98%} (Gy)	57.31 ± 5.18	57.34 ± 5.18	0.765
D _{95%} (Gy)	58.50 ± 3.73	58.50 ± 3.73	-
D _{5%} (Gy)	61.47 ± 2.75	61.31 ± 3.35	0.480
D _{2%} (Gy)	61.72 ± 2.75	61.55 ± 3.35	0.486
Homogeneity index	0.075 ± 0.052	0.072 ± 0.046	0.518
Conformity index	1.008 ± 0.032	1.001 ± 0.029	0.226

DV parameter, dose–volumetric parameter; D_{n%}, dose received by at least *n*% volume of the planning target volume.; VMAT, volumetric modulated arc therapy.

plans indicated that the delivered doses to OARs were always less than the tolerance levels except for the heart. For a total of 8 patients from 20 patients, CPA VMAT plans did not meet the tolerance level of the heart. However, all the NPA VMAT plans meet the tolerance levels of every OAR including the heart in the present study. Moreover, Darby et al demonstrated that the rates of major coronary events increased linearly with the mean

dose to the heart by 7.4% per Gy with no threshold.¹⁵ According to that study by Darby et al, the NPA VMAT plans could reduce the risk of major coronary events by 3.7% on average compared to the CPA VMAT plans. Except the ipsilateral lung, the NPA VMAT plans could reduce not only doses to the heart but also doses to other OARs compared to the CPA VMAT plans, while keeping target coverages identical to those of CPA VMAT plans.

Table 2. Dose–volumetric parameters of the lungs

DV parameter	Coplanar VMAT	Non-coplanar VMAT	<i>p</i>
Right lung (contralateral lung)			
Mean dose (Gy)	1.11 ± 0.45	0.86 ± 0.34	<0.001
D _{1500cc} (Gy)	0.05 ± 0.07	0.04 ± 0.06	0.005
D _{1000cc} (Gy)	0.20 ± 0.12	0.17 ± 0.10	<0.001
V _{20Gy} (cm ³)	0.00 ± 0.00	0.00 ± 0.00	0.330
V _{10Gy} (cm ³)	0.47 ± 1.56	0.16 ± 0.66	0.150
V _{5Gy} (cm ³)	29.21 ± 38.08	8.12 ± 14.72	0.002
Left lung (ipsilateral lung)			
Mean dose (Gy)	5.58 ± 2.50	5.90 ± 2.71	<0.001
D _{1500cc} (Gy)	0.07 ± 0.18	0.07 ± 0.19	0.090
D _{1000cc} (Gy)	0.26 ± 0.36	0.32 ± 0.51	0.085
V _{20Gy} (cm ³)	95.69 ± 63.82	99.75 ± 72.58	0.132
V _{10Gy} (cm ³)	205.85 ± 102.36	211.01 ± 114.39	0.249
V _{5Gy} (cm ³)	325.61 ± 108.83	351.18 ± 130.82	0.001
Both lungs			
Mean dose (Gy)	3.16 ± 1.33	3.17 ± 1.37	0.727
D _{1500cc} (Gy)	0.48 ± 0.35	0.49 ± 0.39	0.776
D _{1000cc} (Gy)	1.21 ± 0.76	1.21 ± 0.73	0.910
V _{20Gy} (cm ³)	95.69 ± 63.81	99.75 ± 72.58	0.132
V _{10Gy} (cm ³)	206.33 ± 102.13	211.16 ± 114.26	0.279
V _{5Gy} (cm ³)	354.86 ± 127.63	359.34 ± 135.22	0.534

DV parameter, dose–volumetric parameter; D_{ncc}, dose received by at least *n* cm³ volume of a structure; VMAT, volumetric modulated arc therapy; V_{nGy}, absolute vol in cm³ receiving *n* Gy.

Table 3. Dose–volumetric parameters of OARs

DV parameter	Coplanar VMAT	Non-coplanar VMAT	<i>p</i>
Heart			
Maximum dose (Gy)	32.40 ± 14.33	25.72 ± 12.26	<0.001
Mean dose (Gy)	2.85 ± 1.93	2.34 ± 1.72	<0.001
D _{0.1cc} (Gy)	29.42 ± 13.37	21.71 ± 9.20	<0.001
D _{2%} (Gy)	15.10 ± 6.75	12.53 ± 6.49	<0.001
V _{34Gy} (cm ³)	1.13 ± 2.23	0.00 ± 0.01	0.041
V _{28Gy} (cm ³)	2.51 ± 4.11	1.72 ± 3.30	0.004
V _{20Gy} (cm ³)	31.04 ± 10.59	24.32 ± 8.04	<0.001
V _{10Gy} (cm ³)	143.01 ± 43.18	110.68 ± 36.19	<0.001
Esophagus			
Mean dose (Gy)	1.57 ± 0.81	1.22 ± 0.58	<0.001
V _{30Gy} (cm ³)	0.00 ± 0.00	0.00 ± 0.00	-
V _{18.8 Gy} (cm ³)	0.01 ± 0.02	0.00 ± 0.00	0.330
Trachea and bronchi			
D _{2%} (Gy)	12.41 ± 8.46	10.76 ± 7.54	0.006
D _{0.1cc} (Gy)	15.47 ± 10.64	13.99 ± 10.67	0.023
V _{34.8 Gy} (cm ³)	0.02 ± 0.06	0.02 ± 0.09	0.623
V _{15.6 Gy} (cm ³)	1.14 ± 2.45	0.75 ± 1.77	0.073
Spinal cord			
Maximum dose (Gy)	6.44 ± 2.41	5.27 ± 1.97	<0.001
D _{0.1cc} (Gy)	6.05 ± 2.26	4.90 ± 1.83	<0.001
D _{2%} (Gy)	5.56 ± 2.02	4.43 ± 1.60	<0.001
V _{26Gy} (cm ³)	0.00 ± 0.00	0.00 ± 0.00	-
V _{20.8Gy} (cm ³)	0.00 ± 0.00	0.00 ± 0.00	-
Skin			
D _{0.1cc} (Gy)	24.70 ± 5.56	22.57 ± 6.12	0.002
D _{2%} (Gy)	13.97 ± 2.76	12.88 ± 3.07	<0.001
V _{36Gy} (cm ³)	0.00 ± 0.00	0.00 ± 0.00	-
V _{33.2Gy} (cm ³)	0.00 ± 0.00	0.00 ± 0.00	-
Stomach			
V _{27.2Gy} (cm ³)	0.00 ± 0.00	0.00 ± 0.00	-
V _{17.6Gy} (cm ³)	0.01 ± 0.02	0.01 ± 0.03	0.330

DV parameter, dose–volumetric parameter; D_{ncc}, dose received by at least *n* cm³ volume of a structure; VMAT, volumetric modulated arc therapy; V_{nGy}, absolute vol in cm³ receiving *n* Gy.

Although doses to the ipsilateral lung increased for NPA VMAT plans compared to those of CPA VMAT plans, doses to the contralateral lung decreased; therefore, no statistically significant differences in the delivered doses were observed for the whole lungs between the NPA and CPA VMAT plans. Moreover, the NPA VMAT plans could reduce whole body doses and could generate steeper dose gradients between the isodose surface of the prescription dose and the isodose surface of the half of the prescription dose than the CPA VMAT plans.¹⁴ Therefore, it seems promising to apply NPA VMAT plans for lung SABR to

particular cases when the tumors are proximal to heart and not concealed by the heart from the anterior view.

The results of the present study were different from those of the previous studies on NPA VMAT and for particular studies, the results were rather contradictory to those of the previous studies.^{3–7} For example, Fleckenstein et al reported a significant reduction of V_{10Gy} of the ipsilateral lung by NPA⁵; however, we found an increase in V_{10Gy} of the ipsilateral lung by NPA although it was not statistically significant. This was because the NPA

Table 4. Dose–volumetric parameters of the body

DV parameter	Coplanar VMAT	Non-coplanar VMAT	<i>p</i>
Mean dose (Gy)	1.2 ± 0.5	1.1 ± 0.5	<0.001
V _{10%} (cm ³)	1201.4 ± 583.0	1081.4 ± 548.4	<0.001
V _{30%} (cm ³)	263.2 ± 159.1	239.0 ± 153.8	<0.001
V _{50%} (cm ³)	104.9 ± 63.2	98.9 ± 62.1	<0.001
V _{70%} (cm ³)	56.9 ± 34.4	55.2 ± 34.3	0.020
V _{90%} (cm ³)	36.4 ± 23.1	35.5 ± 23.0	0.063
Gradient index	4.356 ± 0.608	4.111 ± 0.480	<0.001

DV parameter, dose–volumetric parameter; VMAT, volumetric modulated arc therapy; V_{n%}, absolute vol in cm³ receiving *n*% of the prescription dose.

configurations and tumor locations in the lungs of each study were different from one another.^{3–7} Therefore, direct comparisons among the NPA VMAT studies are not reasonable because the NPA VMAT plan quality varies significantly according to the NPA configuration and the tumor location. In contrast with the previous studies on NPA VMAT, we only enrolled patients with lung tumors close to the heart and utilized the NPA to reduce doses to the heart in the present study.^{3–7} In this way, the mean doses to the heart could be reduced by 22% with NPA compared to those of CPA VMAT plans with the NPA configuration of the present study.

In the present study, we demonstrated better plan quality of the NPA VMAT plans than that of the CPA VMAT plans. However, NPA VMAT plans generally have problems such as collision between the patient (or couch) and the gantry head (*i.e.* clearance problem), longer treatment time than that of the CPA VMAT plans, and potentially large patient setup uncertainty by couch rotation. To avoid the clearance problem, we only utilized anterior NPA rotating from 315° to 45°, which showed no clearance problem at all. Therefore, the results of the present study can only be valid for the limited cases when the tumors are not concealed by the heart to utilize the anterior NPA. If the tumors are located posterior to the heart, the posterior NPA should be applied to take advantage of the NPA; however, it would be hardly applicable to most of VMAT cases in the clinical setting owing to the clearance problem, *i.e.* collision between the patient couch and the gantry head.¹⁶ To apply posterior NPA, a robotic couch with 6 degree of freedom would be a potential solution.¹⁷ By rotating a patient on the robotic couch or lifting the robotic couch upper the isocenter, more space for the application of the posterior NPA might be secured. Actually, roll-rotating a patient with the robotic couch by ±20° is already applied in the field of carbon ion therapy with fixed beam ports to secure more beam–incident–angles to

a patient.¹⁸ To shorten the treatment time of the NPA VMAT plans, we utilized a single quarter NPA requiring a single couch kick in this study. The additional time to rotate the couch in this study would take only few minutes. For the NPA VMAT plans, there might be a risk of patient setup errors by the couch rotation and these errors could not be identified with the CBCT or planar on-board imaging owing to the clearance problem. Therefore, to successfully apply the NPA VMAT technique in the clinical setting, the patient setup after the couch rotation should be verified. Surface imaging systems such as AlignRT (Vision RT Ltd., London, UK) could be a feasible solution for the patient setup verification after the couch rotation.

CONCLUSIONS

In the present study, VMAT plans with an anterior non-coplanar quarter arc by gantry rotations from 315° to 45° combined with couch rotations of around 315° ± 5° showed more favorable plan quality than the CPA VMAT plans for the challenging cases of lung SABR with tumors located close to the heart. The NPA VMAT plans could be applied only to a particular situation when the tumors were not concealed by the heart from the anterior view to utilize the anterior NPA avoiding irradiation of the heart. To successfully implement the NPA VMAT technique in the clinical setting, patient setup verification after the couch rotation is recommended.

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REFERENCES

1. Fakiris AJ, McGarry RC, Yiannoutsos CT, Papiez L, Williams M, Henderson MA, et al. Stereotactic body radiation therapy for early-stage non-small-cell lung carcinoma: four-year results of a prospective phase II study. *Int J Radiat Oncol Biol Phys* 2009; 75: 677–82. doi: <https://doi.org/10.1016/j.ijrobp.2008.11.042>
2. Timmerman R, Paulus R, Galvin J, Michalski J, Straube W, Bradley J, et al. Stereotactic body radiation therapy for inoperable early stage lung cancer. *JAMA* 2010; 303: 1070–6. doi: <https://doi.org/10.1001/jama.2010.261>
3. Dong P, Lee P, Ruan D, Long T, Romeijn E, Low DA, et al. 4π noncoplanar stereotactic

- body radiation therapy for centrally located or larger lung tumors. *Int J Radiat Oncol Biol Phys* 2013; **86**: 407–13. doi: <https://doi.org/10.1016/j.ijrobp.2013.02.002>
4. Fitzgerald R, Owen R, Hargrave C, Pryor D, Barry T, Lehman M, et al. A comparison of three different VMAT techniques for the delivery of lung stereotactic ablative radiation therapy. *J Med Radiat Sci* 2016; **63**: 23–30. doi: <https://doi.org/10.1002/jmrs.156>
 5. Fleckenstein J, Boda-Heggemann J, Siebenlist K, Gudzhewa T, Prakofyeva N, Lohr F, et al. Non-coplanar VMAT combined with non-uniform dose prescription markedly reduces lung dose in breath-hold lung SBRT. *Strahlenther Onkol* 2018; **194**: 815–23. doi: <https://doi.org/10.1007/s00066-018-1316-0>
 6. Ishii K, Okada W, Ogino R, Kubo K, Kishimoto S, Nakahara R, et al. A treatment-planning comparison of three beam arrangement strategies for stereotactic body radiation therapy for centrally located lung tumors using volumetric-modulated Arc therapy. *J Radiat Res* 2016; **57**: 273–9. doi: <https://doi.org/10.1093/jrr/rrv105>
 7. Yu AS, Maxim PG, Loo BW, Gensheimer MF. Chest wall dose reduction using noncoplanar volumetric modulated Arc radiation therapy for lung stereotactic ablative radiation therapy. *Pract Radiat Oncol* 2018; **8**: e199–207. doi: <https://doi.org/10.1016/j.prro.2017.12.005>
 8. Qian Y, Zhu H, Pollom EL, Durkee BY, Chaudhuri AA, Gensheimer MF, et al. Sinoatrial node toxicity after stereotactic ablative radiation therapy to lung tumors. *Pract Radiat Oncol* 2017; **7**: e525–9. doi: <https://doi.org/10.1016/j.prro.2017.04.005>
 9. Yeo S-G, Kim ES. Efficient approach for determining four-dimensional computed tomography-based internal target volume in stereotactic radiotherapy of lung cancer. *Radiat Oncol J* 2013; **31**: 247–51. doi: <https://doi.org/10.3857/roj.2013.31.4.247>
 10. Park JM, Park S-Y, Kim HJ, Wu H-G, Carlson J, Kim J-in. A comparative planning study for lung SABR between tri-Co-60 magnetic resonance image guided radiation therapy system and volumetric modulated Arc therapy. *Radiotherapy and Oncology* 2016; **120**: 279–85. doi: <https://doi.org/10.1016/j.radonc.2016.06.013>
 11. Kim J-in, Han JH, Choi CH, An HJ, Wu H-G, Park JM, et al. Discrepancies in dose-volume histograms generated from different treatment planning systems. *J Radiat Prot Res* 2018; **43**: 59–65. doi: <https://doi.org/10.14407/jrpr.2018.43.2.59>
 12. Shaw E, Kline R, Gillin M, Souhami L, Hirschfeld A, Dinapoli R, et al. Radiation therapy Oncology group: radiosurgery quality assurance guidelines. *Int J Radiat Oncol Biol Phys* 1993; **27**: 1231–9. doi: [https://doi.org/10.1016/0360-3016\(93\)90548-A](https://doi.org/10.1016/0360-3016(93)90548-A)
 13. Zhang P, Happersett L, Hunt M, Jackson A, Zelefsky M, Mageras G. Volumetric modulated Arc therapy: planning and evaluation for prostate cancer cases. *Int J Radiat Oncol Biol Phys* 2010; **76**: 1456–62. doi: <https://doi.org/10.1016/j.ijrobp.2009.03.033>
 14. Paddick I, Lippitz B. A simple dose gradient measurement tool to complement the conformity index. *J Neurosurg* 2006; **105**(Suppl): 194–201. doi: <https://doi.org/10.3171/sup.2006.105.7.194>
 15. Darby SC, Ewertz M, McGale P, Bennet AM, Blom-Goldman U, Brønnum D, et al. Risk of ischemic heart disease in women after radiotherapy for breast cancer. *N Engl J Med* 2013; **368**: 987–98. doi: <https://doi.org/10.1056/NEJMoa1209825>
 16. Becker SJ. Collision indicator charts for gantry-couch position combinations for Varian linacs. *Journal of Applied Clinical Medical Physics* 2011; **12**: 16–22. doi: <https://doi.org/10.1120/jacmp.v12i3.3405>
 17. Collins SP, Coppa ND, Zhang Y, Collins BT, McRae DA, Jean WC. CyberKnife radiosurgery in the treatment of complex skull base tumors: analysis of treatment planning parameters. *Radiat Oncol* 2006; **1**: 46. doi: <https://doi.org/10.1186/1748-717X-1-46>
 18. Uhl M, Edler L, Jensen AD, Habl G, Oelmann J, Röder F, et al. Randomized phase II trial of hypofractionated proton versus carbon ion radiation therapy in patients with sacrococcygeal chordoma-the ISAC trial protocol. *Radiat Oncol* 2014; **9**: 100. doi: <https://doi.org/10.1186/1748-717X-9-100>