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Influence of Delivery Geometry and Beam Modulation on Dose Gradient and Organ-at-Risk Sparing in Lung SBRT: A Comparative Planning Study

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Abstract

Purpose: To compare target coverage, selected plan-quality indices, organ-at-risk (OAR) dose parameters, and planned beam-on delivery time among coplanar VMAT (C-VMAT), non-coplanar VMAT (NC-VMAT), unblocked helical tomotherapy (UB-HT), and directionally blocked helical tomotherapy (DB-HT) in lung stereotactic body radiotherapy (SBRT).
Methods: Ten patients with early-stage non-small cell lung cancer or oligometastatic lung lesions were retrospectively replanned. For each patient, seven plans were generated using the same planning CT dataset and structure set: C-VMAT, four NC-VMAT configurations with couch rotations of 45°, 60°, 75°, and 90°, UB-HT, and DB-HT. Plans were evaluated using target coverage, gradient index (GI), conformity index (CI), homogeneity index (HI), selected OAR dose metrics, and planned beam-on time. Comparisons were performed using the Friedman test.
Results: All techniques achieved clinically acceptable target coverage, with mean PTV V50 coverage close to the planning objective. Although PTV V50 showed a statistically significant overall difference, the absolute differences were small. Significant overall differences were observed for GI and HI, whereas CI did not differ significantly. Planned beam-on time showed the clearest technique-related difference, with VMAT-based plans requiring substantially shorter times than HT-based plans. HT-based plans, particularly DB-HT, showed lower mean lung V20 and mean lung dose values. DB-HT also showed the lowest mean heart and aorta D0.1cc values; however, these findings were interpreted as descriptive overall differences rather than pairwise evidence of superiority.
Conclusion: Under standardized planning conditions, all evaluated techniques produced acceptable lung SBRT plans. VMAT-based techniques provided shorter planned beam-on times, whereas DB-HT showed lower mean values for selected lung and mediastinal OAR parameters. Larger studies with anatomical stratification and spatial gradient metrics are needed to clarify the clinical relevance of these dosimetric differences.

Keywords: Lung SBRT; VMAT; Helical Tomotherapy; Dose Gradient; Treatment Planning.

Introduction

Stereotactic body radiotherapy (SBRT) requires the delivery of ablative radiation doses with high geometric precision, while maintaining rapid dose fall-off outside the target volume and limiting irradiation of surrounding normal tissues[1,2]. In lung SBRT, these requirements are particularly challenging because of tissue heterogeneity, respiratory motion, and the close anatomical relationship between lung lesions and critical thoracic organs such as the spinal cord, esophagus, trachea, heart, aorta, ribs, and chest wall[3,4]. Therefore, treatment plan quality in lung SBRT depends on several interacting factors, including target size, lesion location, dose calculation accuracy, beam geometry, modulation strategy, optimization objectives, and the spatial relationship between the planning target volume (PTV) and organs at risk (OARs).

Modern rotational radiotherapy techniques provide different approaches to achieving conformal dose distributions in lung SBRT. Volumetric-modulated arc therapy (VMAT) combines continuous gantry rotation with dynamic multileaf collimator motion, variable dose rate, and gantry-speed modulation[5,6]. Helical tomotherapy (HT), in contrast, delivers radiation using rotational fan-beam irradiation with couch translation and binary multileaf collimator modulation[7,8]. These technical differences may influence target coverage, dose conformity, OAR sparing, and treatment delivery effi-

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ciency. However, the extent to which delivery geometry and beam modulation strategy affect plan quality remains dependent on patient-specific anatomy and planning objectives.

Non-coplanar beam arrangements have been investigated as a strategy to improve OAR sparing by increasing angular freedom and diversifying beam paths[9,10]. In selected lung SBRT cases, non-coplanar VMAT may reduce dose to nearby thoracic structures by avoiding unfavorable beam directions. Nevertheless, the clinical use of extensive couch rotations may be limited by collision risk, patient clearance, immobilization constraints, and increased setup complexity. For this reason, non-coplanar configurations should be interpreted not only as potential clinical delivery approaches, but also as useful methodological tools for investigating the geometric sensitivity of treatment planning.

Dose fall-off in SBRT is commonly described using global volumetric indices such as the gradient index (GI), while conformity index (CI) and homogeneity index (HI) are used to characterize prescription isodose conformity and dose uniformity within the target volume[1,2,11]. These indices are practical and widely used in stereotactic treatment planning; however, they describe different aspects of plan quality. GI reflects global volumetric dose fall-off around the target, whereas CI and HI primarily describe target conformity and dose homogeneity. Therefore, these parameters should be interpreted as complementary plan-quality descriptors rather than interchangeable measures of dose gradient. In addition, global indices do not directly describe local directional dose fall-off toward individual OARs.

Directionally blocked helical tomotherapy represents another planning strategy that may influence OAR exposure. By restricting beam entrance through selected angular sectors, directional blocking may reduce irradiation through specific anatomical regions and thereby lower dose to selected OARs in some cases[12]. However, the dosimetric impact of directional blocking in lung SBRT may vary according to tumor position, PTV size, and the distance between the PTV and nearby critical organs. Therefore, its potential benefit should be evaluated in relation to patient-specific geometry rather than assumed as a general advantage.

In the present study, each patient was replanned using the same planning CT dataset and identical structure set across seven delivery approaches: coplanar VMAT (C-VMAT), four predefined non-coplanar VMAT (NC-VMAT) configurations with couch rotations of 45°, 60°, 75°, and 90°, unblocked helical tomotherapy, and directionally blocked helical tomotherapy. This within-patient replanning design was used to compare delivery techniques under identical anatomical conditions for each patient and to reduce confounding related to differences in contouring or planning datasets.

The aim of this study was to compare target coverage, selected plan-quality indices, OAR dose parameters, and planned beam-on delivery time among these delivery techniques under standardized planning conditions. In this context, GI was considered a global volumetric descriptor of dose fall-off, whereas CI, HI, OAR dose parameters, and beam-on time were interpreted as separate but complementary indicators of plan quality and treatment efficiency.

Materials and methods

Study design and patient data

This retrospective treatment planning study included planning CT datasets from ten patients previously treated for early-stage non-small cell lung cancer or oligometastatic lung lesions. All datasets were anonymized before analysis, and the study was conducted in accordance with institutional ethical principles for retrospective dosimetric investigations.

For each patient, seven treatment plans were generated using the same planning CT dataset and identical structure set. The evaluated techniques were C-VMAT, four NC-VMAT configurations with couch rotations of 45°, 60°, 75°, and 90°, unblocked helical tomotherapy (UB-HT), and directionally blocked helical tomotherapy (DB-HT). This within-patient replanning design allowed each delivery technique to be compared under identical anatomical conditions for a given patient.

Patient-specific lesion characteristics, including PTV volume, tumor location, nearest organ at risk, and minimum PTV–OAR distance, are summarized in **Table 1**. The minimum PTV–OAR distance was defined as the shortest surface-to-surface distance between the PTV contour and the nearest contoured OAR, as measured on the planning CT dataset using the treatment planning system measurement tools. The nearest OAR was defined as the critical structure with the smallest measured surface-to-surface distance from the PTV. PTV volumes ranged from 3.5 to 44.5 cc. All lesions included in this cohort were classified as peripheral. The nearest OAR was the heart in eight patients and the spinal cord in two patients. These anatomical differences were considered when interpreting OAR dose variations; however, no formal anatomical subgroup analysis was performed because of the limited sample size.

Table 1. Patient and lesion characteristics

Patient	PTV volume (cc)	Location	Nearest OAR and minimum PTV–OAR distance*
1	22.7	Peripheral	Heart: 11.0 cm
2	31.1	Peripheral	Heart: 13.1 cm
3	16.8	Peripheral	Heart: 2.8 cm
4	19.7	Peripheral	Heart: 3.4 cm
5	3.5	Peripheral	Spinal cord: 1.8 cm
6	44.5	Peripheral	Heart: 11.6 cm
7	7.4	Peripheral	Heart: 4.7 cm
8	29.0	Peripheral	Spinal cord: 3.1 cm
9	12.0	Peripheral	Heart: 6.3 cm
10	5.5	Peripheral	Heart: 7.0 cm

*The minimum PTV–OAR distance was defined as the shortest surface-to-surface distance between the PTV contour and the nearest contoured OAR, measured on the planning CT dataset using the treatment planning system measurement tools.

Imaging and Structure Delineation

All treatment plans were based on planning CT images acquired under standard thoracic simulation conditions. Target volumes

were delineated according to established SBRT contouring principles, including gross tumor volume and planning target volume definitions consistent with stereotactic radiotherapy guidelines[1,2]. Organs at risk, including total lung, spinal cord, esophagus, trachea, heart, aorta, ribs or chest wall, and liver where applicable, were contoured using standard thoracic contouring practice and consensus-based anatomical guidance[13].

Because steep dose gradients are characteristic of SBRT, particular attention was given to contouring consistency and spatial definition of target and OAR boundaries. Contouring was performed on the same structure set for all replanned techniques in each patient to avoid contour-related differences among plans.

Treatment Planning and Dose Calculation

All treatment plans were prescribed 50 Gy in five fractions, corresponding to 10 Gy per fraction, consistent with commonly used lung SBRT regimens[3]. For each patient, all plans were optimized to achieve clinically acceptable target coverage while respecting institutional OAR constraints.

VMAT plans were generated using the Monaco Treatment Planning System (Elekta AB, Stockholm, Sweden), employing a GPU-accelerated Monte Carlo dose calculation algorithm. Monte Carlo-based dose calculation is particularly relevant in lung SBRT because of tissue heterogeneity, electronic disequilibrium effects in low-density lung regions, and the dosimetric challenges associated with small photon fields[14,15]. C-VMAT plans were generated with the couch angle fixed at 0°. NC-VMAT plans were generated using predefined couch rotations of 45°, 60°, 75°, and 90°. These non-coplanar configurations were used as a methodological approach to evaluate geometric sensitivity and should not be interpreted as routine clinical delivery protocols.

HT plans were generated using the Precision Treatment Planning System (Accuray Inc., Sunnyvale, CA, USA). UB-HT plans were created without directional beam blocking. DB-HT plans were created using directional blocking to restrict beam entrance through selected angular sectors with the aim of reducing irradiation through selected OAR regions. For HT planning, field width, pitch, and modulation factor were kept constant across patients as far as clinically achievable. The field width was 2.5 cm, the pitch was 0.287, and the modulation factor ranged from 2.0 to 3.0 according to standard clinical planning practice.

It should be noted that VMAT and HT plans were calculated using different treatment planning systems and dose calculation algorithms. This reflects routine clinical implementation of these platforms, but it also limits strict isolation of delivery geometry from platform-specific planning and dose calculation effects. Therefore, the comparison should be interpreted as a practical planning comparison among clinically implemented delivery approaches rather than as a pure physics comparison of beam geometry alone.

Planning Objectives and Optimization Strategy

All plans were generated using standardized planning objectives. Target coverage was prioritized to achieve approximately 95% of the prescription dose to at least 95% of the PTV. OAR sparing objectives were applied according to institutional lung SBRT planning practice and published dose-constraint guidance[1,16]. Additional auxiliary structures, including ring structures around the PTV, were used where needed to support dose fall-off and improve conformity.

The institutional OAR constraints used for plan evaluation included spinal cord D0.035cc < 25.3 Gy, total lung V20 < 10%, mean lung dose < 8 Gy, aorta D0.1cc < 60 Gy, chest wall D30cc < 30 Gy, esophagus D0.1cc < 40 Gy, trachea D0.1cc < 38 Gy, heart D0.1cc < 40 Gy, and, where applicable, liver D700cc < 15 Gy, liver V10 < 70%, and mean liver dose < 15.2 Gy. These constraints were used to guide and contextualize plan acceptability. They were not used as strict endpoints for determining superiority among techniques.

Delivery Techniques

C-VMAT plans were designed using continuous gantry rotation in a coplanar geometry with the couch fixed at 0°. NC-VMAT plans used predefined couch rotations of 45°, 60°, 75°, and 90°, thereby increasing angular degrees of freedom. However, these non-coplanar plans were primarily included to investigate the effect of delivery geometry under controlled planning conditions. In clinical practice, large couch rotations may be limited by collision risk, patient clearance, immobilization limitations, and increased setup complexity.

UB-HT plans were generated using helical fan-beam delivery with couch translation and binary multileaf collimator modulation[7,8]. DB-HT plans used the same helical delivery concept, but with directional blocking applied to selected angular sectors. Directional blocking was evaluated as a beam-path modulation strategy that may reduce exposure of selected mediastinal OARs in specific anatomical situations[12].

Plan Quality Assessment and Dosimetric Evaluation

Plan quality was evaluated using target coverage parameters, target-related plan-quality indices, OAR dose parameters, and planned beam-on delivery time. Target coverage and target-related indices are summarized in **Table 2**. Planned beam-on delivery time is summarized in **Table 3**. Lung and serial thoracic OAR parameters are summarized in **Table 4**, mediastinal OAR high-dose parameters in **Table 5,** and chest wall/rib and liver dose parameters in **Table 6**.

The gradient index was defined as the ratio between the volume receiving 50% of the prescription dose and the PTV volume. For the present prescription of 50 Gy, GI was calculated as V25Gy/PTV. Lower GI values indicate a steeper global dose fall-off outside the target volume. In this study, GI was interpreted as a global volumetric descriptor of dose fall-off and not as a local or directional gradient metric toward individual OARs.

Table 2. Target coverage and target-related plan-quality indices

Parameter	PTV V50 Gy (%)	PTV V45 Gy (%)	GI	CI	HI	PTV Dmax (cGy)
C-VMAT	95.00 ± 0.01	100.00 ± 0.00	5.14 ± 0.71	0.89 ± 0.03	0.13 ± 0.03	5712 ± 292
NC-VMAT 45°	95.00 ± 0.01	100.00 ± 0.00	5.07 ± 0.65	0.88 ± 0.04	0.13 ± 0.03	5823 ± 180
NC-VMAT 60°	95.00 ± 0.01	100.00 ± 0.00	4.93 ± 0.61	0.88 ± 0.03	0.13 ± 0.02	5758 ± 127
NC-VMAT 75°	95.00 ± 0.01	100.00 ± 0.00	4.85 ± 0.62	0.88 ± 0.04	0.12 ± 0.03	5792 ± 178
NC-VMAT 90°	95.00 ± 0.01	100.00 ± 0.00	4.89 ± 0.63	0.88 ± 0.04	0.11 ± 0.02	5809 ± 124
UB-HT	94.76 ± 0.18	99.98 ± 0.04	4.87 ± 0.81	0.89 ± 0.04	0.16 ± 0.02	5951 ± 110
DB-HT	94.83 ± 0.14	99.99 ± 0.03	5.01 ± 0.80	0.89 ± 0.02	0.13 ± 0.04	5834 ± 190
p-value	<0.001	0.267	<0.001	0.871	0.025	0.199

Table 3. Planned beam-on delivery time

Parameter	Planned beam-on time (s)
C-VMAT	219 ± 28
NC-VMAT 45°	214 ± 43
NC-VMAT 60°	220 ± 45
NC-VMAT 75°	220 ± 42
NC-VMAT 90°	219 ± 34
UB-HT	816 ± 228
DB-HT	951 ± 261
p-value	<0.001

Table 5. Mediastinal OAR high-dose parameters

Parameter	Aorta D0.1cc (cGy)	Heart D0.1cc (cGy)
C-VMAT	900 ± 389	1070 ± 651
NC-VMAT 45°	907 ± 368	1075 ± 453
NC-VMAT 60°	899 ± 375	1131 ± 457
NC-VMAT 75°	857 ± 330	1033 ± 474
NC-VMAT 90°	867 ± 326	945 ± 507
UB-HT	723 ± 269	801 ± 522
DB-HT	579 ± 264	780 ± 475
p-value	0.013	0.009

Table 4. Lung and serial thoracic OAR dose parameters

Parameter	Lung V20 (%)	Mean lung dose (cGy)	Spinal cord D0.1cc (cGy)	Esophagus D0.1cc (cGy)	Trachea D0.1cc (cGy)
C-VMAT	2.92 ± 2.17	297 ± 144	1024 ± 433	831 ± 197	715 ± 917
NC-VMAT 45°	2.89 ± 2.21	303 ± 155	1000 ± 552	807 ± 207	691 ± 906
NC-VMAT 60°	2.82 ± 2.16	301 ± 151	990 ± 488	833 ± 193	669 ± 895
NC-VMAT 75°	2.75 ± 2.13	305 ± 153	955 ± 467	800 ± 213	643 ± 865
NC-VMAT 90°	2.77 ± 2.10	304 ± 145	969 ± 480	786 ± 216	628 ± 828
UB-HT	2.61 ± 1.99	279 ± 143	933 ± 455	887 ± 158	635 ± 812
DB-HT	2.57 ± 1.77	255 ± 127	799 ± 299	741 ± 177	568 ± 732
p-value	<0.001	<0.001	0.101	0.176	0.482

Table 6. Chest wall/rib and liver dose parameters

Parameter	Rib D0.1cc (cGy)	Rib / chest wall D30cc (cGy)	Liver D700cc (cGy)	Liver V10 (%)
C-VMAT	4484 ± 1299	1730 ± 621	19 ± 35	2.97 ± 4.53
NC-VMAT 45°	4486 ± 1323	1772 ± 645	25 ± 44	3.91 ± 6.26
NC-VMAT 60°	4457 ± 1348	1741 ± 640	24 ± 42	3.23 ± 5.38
NC-VMAT 75°	4408 ± 1396	1728 ± 641	24 ± 45	3.04 ± 4.55
NC-VMAT 90°	4429 ± 1350	1726 ± 672	23 ± 42	4.08 ± 5.21
UB-HT	4391 ± 1570	1754 ± 685	69 ± 109	2.33 ± 3.69
DB-HT	4294 ± 1537	1798 ± 698	68 ± 106	2.67 ± 4.09
p-value	0.131	0.048	<0.001	0.001

The conformity index and homogeneity index were used as additional target-related plan-quality indices. CI was used to evaluate prescription isodose conformity, whereas HI was used to characterize dose uniformity within the PTV[2,11]. GI, CI, and HI were interpreted as complementary descriptors of plan quality rather than interchangeable measures of dose gradient.

OAR dose parameters were extracted from dose-volume histogram analysis. Evaluated OAR metrics included total lung V20, mean lung dose, spinal cord D0.1cc, esophagus D0.1cc, trachea D0.1cc, heart D0.1cc, aorta D0.1cc, rib D0.1cc, chest wall or rib D30cc, and liver dose parameters where applicable. Liver D700cc and liver V10 were evaluated descriptively because liver dose assessment was clinically relevant only for inferior thoracic treatment geometries in which the liver was included within the relevant scan and dose region.

Planned beam-on delivery time was defined as the treatment delivery time reported by the treatment planning or delivery system. It was recorded in seconds and did not include patient setup, image guidance, couch rotation, or repositioning time.

To reduce redundancy in the main manuscript, patient-level dosimetric values were summarized as mean ± standard deviation for each delivery technique. Detailed patient-level values may be provided as supplementary material.

Statistical Analysis

Statistical analysis was performed using non-parametric methods because of the limited sample size and repeated-measures study design. Since each patient was planned using all seven delivery techniques, comparisons among techniques were performed using the Friedman test for repeated measures. The evaluated techniques were C-VMAT, NC-VMAT 45°, NC-VMAT 60°, NC-VMAT 75°, NC-VMAT 90°, UB-HT, and DB-HT.

Continuous variables are presented as mean ± standard deviation. A p-value of < 0.05 was considered statistically significant. No pairwise post-hoc comparisons were used to establish superiority between individual techniques. Therefore, statistically significant Friedman test results were interpreted only as evidence of an overall difference among techniques. Because of the small cohort size, statistically significant findings were interpreted cautiously and were not considered sufficient by themselves to establish clinical superiority of one technique over another. Because multiple dosimetric endpoints were tested in this exploratory planning study, p-values were interpreted as nominal and hypothesis-generating rather than as confirmatory evidence of clinical superiority.

Results

Patient and lesion characteristics are summarized in **Table 1**. The PTV volume ranged from 3.5 to 44.5 cc. All lesions included in this cohort were classified as peripheral. The nearest OAR was the heart in eight patients and the spinal cord in two patients. The minimum surface-to-surface PTV–OAR distance ranged from 1.8 to 13.1 cm, demonstrating considerable variation in the spatial relationship between the target and the nearest critical structure. However, because of the limited sample size, no formal subgroup analysis was performed according to PTV volume, nearest OAR, or PTV-OAR distance.

Target coverage and target-related plan-quality indices are presented in **Table 2**. All evaluated techniques achieved clinically acceptable target coverage under the standardized planning conditions used in this study. Mean PTV V50 Gy (%) values were close to the planning objective for all techniques, ranging from 94.76 ± 0.18% for UB-HT to 95.00 ± 0.01% for NC-VMAT 75°. Although the Friedman test showed a statistically significant overall difference in PTV V50 Gy (%) among techniques ($p < 0.001$), the absolute magnitude of this difference was small. PTV V45 Gy (%) remained close to 100% for all techniques and did not differ significantly among techniques ($p = 0.267$).

GI showed a statistically significant overall difference among techniques ($p < 0.001$). The lowest mean GI value was observed for NC-VMAT 75° (4.85 ± 0.62), followed by UB-HT (4.87 ± 0.81) and NC-VMAT 90° (4.89 ± 0.63). C-VMAT and DB-HT showed mean GI values of 5.14 ± 0.71 and 5.01 ± 0.80, respectively. Although these differences were statistically detectable, the GI results should be interpreted cautiously because GI is a global volumetric descriptor of dose fall-off and does not provide information about local directional gradients toward individual OARs.

CI values remained similar across the evaluated techniques and did not show a statistically significant difference ($p = 0.871$). Mean CI values ranged from 0.88 ± 0.04 for NC-VMAT 75° to 0.89 ± 0.04 for UB-HT. HI showed a statistically significant overall difference among techniques ($p = 0.025$), with the lowest mean value observed for NC-VMAT 90° (0.11 ± 0.02) and the highest mean value observed for UB-HT (0.16 ± 0.02). Maximum PTV dose values did not differ significantly among techniques ($p = 0.199$).

Planned beam-on delivery time is summarized in **Table 3**. A statistically significant overall difference was observed among techniques ($p < 0.001$). VMAT-based techniques showed substantially shorter planned beam-on times than HT-based techniques. Mean beam-on times for VMAT-based plans ranged from 214 ± 43 s for NC-VMAT 45° to 220 ± 42 s for NC-VMAT 75°. In contrast, the mean planned beam-on time was 816 ± 228 s for UB-HT and 951 ± 261 s for DB-HT. This represented the most pronounced technique-related difference observed in the present study.

Lung and serial thoracic OAR dose parameters are presented in **Table 4**. Lung V20 differed significantly among techniques ($p < 0.001$). The lowest mean lung V20 value was observed for DB-HT (2.57 ± 1.77%), followed by UB-HT (2.61 ± 1.99%). VMAT-based techniques showed slightly higher mean lung V20 values, ranging from 2.75 ± 2.13% for NC-VMAT 75° to 2.92 ± 2.17% for C-VMAT. Mean lung dose also differed significantly among techniques ($p < 0.001$). DB-HT showed the lowest mean lung dose (255 ± 127 cGy), followed by UB-HT

(279 ± 143 cGy), whereas VMAT-based techniques showed mean values between 297 ± 144 cGy and 305 ± 153 cGy.

For serial thoracic OARs, spinal cord, esophagus, and trachea dose parameters did not show statistically significant differences among techniques. Spinal cord D0.1cc was lowest on average for DB-HT (799 ± 299 cGy), but the overall difference among techniques was not statistically significant ($p = 0.101$). Esophagus D0.1cc also did not differ significantly ($p = 0.176$), although DB-HT showed the lowest mean value (741 ± 177 cGy). Trachea D0.1cc showed wide variability across cases, but no significant overall difference among techniques was observed ($p = 0.482$).

Mediastinal OAR high-dose parameters are summarized in **Table 5**. Aorta D0.1cc differed significantly among techniques ($p = 0.013$). DB-HT showed the lowest mean aorta D0.1cc value (579 ± 264 cGy), followed by UB-HT (723 ± 269 cGy), whereas VMAT-based techniques showed higher mean values. Heart D0.1cc also differed significantly among techniques ($p = 0.009$). The lowest mean heart D0.1cc value was observed for DB-HT (780 ± 475 cGy), followed by UB-HT (801 ± 522 cGy). These results indicate that DB-HT showed lower mean values for selected mediastinal OAR high-dose parameters in this cohort. However, because no corrected pairwise post-hoc comparison or formal anatomical subgroup analysis was performed, this observation should be interpreted as descriptive and hypothesis-generating.

Chest wall/rib and liver dose parameters are presented in **Table 6**. Rib D0.1cc did not differ significantly among techniques ($p = 0.131$). Rib/chest wall D30cc showed a statistically significant but marginal overall difference among techniques ($p = 0.048$). Because the mean values were relatively close across techniques, and because no corrected pairwise post-hoc analysis was performed, this finding should not be interpreted as evidence of a clear technique-related advantage.

Liver dose parameters showed statistically significant overall differences among techniques, with $p < 0.001$ for liver D700cc and $p = 0.001$ for liver V10. However, liver-related findings should be interpreted descriptively, because liver dose assessment was clinically relevant only in inferior thoracic geometries where the liver was included within the relevant scan and dose region. Therefore, liver parameters were not considered primary comparative endpoints in this study.

Overall, the results indicate that all evaluated techniques achieved clinically acceptable target coverage. Statistically significant overall differences were observed for selected parameters, including PTV V50 coverage, GI, HI, planned beam-on time, lung V20, mean lung dose, aorta D0.1cc, heart D0.1cc, and liver-related parameters. Among these, the most pronounced technique-related difference was planned beam-on delivery time, which was substantially shorter for VMAT-based techniques. HT-based techniques, particularly DB-HT, showed lower mean values for selected lung and mediastinal OAR parameters, but these findings should be interpreted cautiously because of the small cohort size and absence of formal anatomical subgroup analysis.

Discussion

This comparative planning study evaluated target coverage, selected plan-quality indices, OAR dose parameters, and planned beam-on delivery time across C-VMAT, four NC-VMAT configurations, UB-HT, and DB-HT techniques in lung SBRT. All evaluated techniques achieved clinically acceptable target coverage under standardized planning conditions. Statistically significant overall differences were observed for selected parameters, including PTV V50 coverage, GI, HI, planned beam-on time, lung V20, mean lung dose, aorta D0.1cc, and heart D0.1cc. However, the clinical interpretation of these differences requires caution because of the small cohort size, the limited absolute magnitude of some differences, and the absence of formal anatomical subgroup analysis.

Target coverage was maintained close to the clinical planning objective for all techniques. Although PTV V50 coverage showed a statistically significant overall difference, the absolute difference among techniques was small, with mean values remaining close to 95% in all plans. Therefore, this statistical significance should not be interpreted as clinically meaningful under the present planning conditions. PTV V45 Gy did not differ significantly among techniques, indicating comparable target-volume coverage at the 45-Gy dose level across all planning approaches. These findings indicate that all planning approaches were able to satisfy the target coverage requirements used in this study.

The present results showed a statistically significant overall difference in GI among techniques. The lowest mean GI values were observed for NC-VMAT 75°, UB-HT, and NC-VMAT 90°, suggesting slightly steeper global volumetric dose fall-off in these plans. However, the GI results should be interpreted cautiously. It is a global volumetric descriptor of dose fall-off and does not provide information about the direction of dose fall-off, the local spatial gradient toward a specific OAR, or the relationship between the prescription isodose and individual critical structures. Therefore, even when statistically significant GI differences are observed, they should not be considered sufficient by themselves to establish the clinical superiority of one delivery technique over another. This interpretation is consistent with SBRT plan evaluation principles, in which conformity, dose fall-off, target coverage, and OAR constraints are considered complementary plan-quality descriptors[1,2].

CI did not differ significantly among the evaluated techniques, indicating that prescription isodose conformity was broadly comparable under the standardized planning approach. In contrast, HI showed a statistically significant overall difference, with UB-HT showing the highest mean HI and NC-VMAT 90° showing the lowest mean HI. Since HI reflects dose uniformity within the PTV rather than dose fall-off outside the target, it should be discussed separately from gradient behaviour. The observed HI difference may reflect differences in optimization and dose modulation characteristics among platforms, but because post-hoc pairwise comparisons were not used as primary evidence of superiority, this result should be interpreted as an overall statistical difference rather than as proof of a clinically relevant advantage for any single technique.

The most pronounced technique-related difference in this study was planned beam-on delivery time. VMAT-based plans showed substantially shorter planned beam-on times than HT-based plans. This finding is expected from the different delivery mechanisms of VMAT and HT. VMAT delivers radiation through continuous gantry rotation with dynamic multileaf collimator motion, variable dose rate, and gantry-speed modulation[5,6], whereas HT uses helical fan-beam delivery with couch translation and binary multileaf collimator modulation[7,8]. Shorter beam-on time may be clinically relevant because it can improve treatment efficiency, patient comfort, and potentially reduce the risk of intrafraction motion. Nevertheless, the present study recorded only planned beam-on time and did not include setup, image guidance, couch rotation, or repositioning time. Therefore, treatment efficiency should be interpreted within this limitation.

For lung dose parameters, HT-based plans, particularly DB-HT, showed lower mean lung V20 and mean lung dose values than VMAT-based plans. Both lung V20 and mean lung dose differed significantly among techniques. This finding suggests that helical delivery and directional beam modulation may reduce low- to intermediate-dose exposure to the lung in some planning situations. However, the absolute values of lung V20 and mean lung dose were low across all techniques and remained within institutional constraints. Therefore, while the differences were statistically detectable, their clinical relevance should be evaluated cautiously, particularly in a small cohort with only peripheral lesions.

For serial thoracic OARs, spinal cord, esophagus, and trachea D0.1cc values did not show statistically significant differences among techniques. Although DB-HT showed lower mean values for spinal cord and esophagus D0.1cc, the variability across cases was broad. This variability may partly reflect case-specific differences in the surface-to-surface distance between the PTV and nearby OARs. However, the relationship between PTV–OAR distance and the corresponding OAR dose was not formally evaluated because of the limited sample size. Therefore, these observations should be interpreted descriptively rather than as evidence of a reproducible technique-specific advantage.

Aorta and heart D0.1cc values differed significantly among techniques, with DB-HT showing the lowest mean values for both parameters. This result is physically plausible because directional blocking restricts beam entrance through selected angular sectors and may reduce irradiation through mediastinal structures. The lower mean values observed for selected mediastinal high-dose parameters suggest that DB-HT may be advantageous in some anatomical scenarios where the heart or aorta is close to the high-dose region. However, this conclusion should not be overstated. The present cohort included only ten patients and all lesions were classified as peripheral. Moreover, no formal stratification was performed according to PTV–heart distance, PTV-aorta distance, or central versus peripheral tumor location. Therefore, the lower heart and aorta D0.1cc values with DB-HT should be regarded as descriptive and hypothesis-generating rather than definitive evidence of general clinical superiority.

Rib D0.1cc did not differ significantly among techniques, whereas rib/chest wall D30cc showed a statistically significant but marginal overall difference. Because the mean values were relatively close across techniques and because chest wall dose is strongly influenced by lesion proximity to the thoracic wall, this marginal overall difference should be interpreted cautiously. Without anatomical stratification and post-hoc analysis, it is not possible to determine whether the observed difference reflects a true delivery-technique effect or case-specific geometry.

Liver dose parameters showed statistically significant overall differences among techniques. However, these results require particularly cautious interpretation. Liver dose assessment is clinically meaningful mainly for inferior thoracic lesions where the liver is included within the relevant treatment geometry and dose region. In the present dataset, several liver values were close to zero, indicating that liver exposure was not equally relevant across all patients. Therefore, liver D700cc and liver V10 were considered descriptive parameters rather than primary comparative endpoints. Future studies focusing specifically on inferior lung lesions may be required to evaluate the relevance of liver dose differences among delivery techniques.

The present results highlight the importance of distinguishing statistical significance from clinical relevance. Several parameters showed statistically significant differences among techniques, but some of these differences were numerically small or occurred in parameters with limited direct clinical interpretability in the absence of subgroup analysis. For example, the statistically significant difference in PTV V50 Gy coverage was not clinically meaningful because all techniques achieved target coverage close to the planning objective. Similarly, GI and HI showed statistically significant differences, but these indices do not directly describe local OAR-specific dose fall-off. For this reason, plan evaluation in lung SBRT should rely on a combination of target coverage, global plan-quality indices, OAR dose metrics, and delivery efficiency rather than on any single index.

Several limitations should be acknowledged. First, the sample size was limited to ten patients, reducing statistical power and preventing formal anatomical stratification. Second, all lesions in this cohort were peripheral; therefore, the findings may not apply directly to centrally located lung tumors, where proximity to mediastinal OARs is more critical. Third, although the within-patient replanning design reduced confounding related to patient anatomy and contouring, the study did not isolate the pure effect of beam geometry from planning system and dose calculation differences. VMAT plans were generated using a Monte Carlo-based calculation algorithm, whereas HT plans were generated using the native HT planning system. This reflects clinical practice but limits strict physical comparison between platforms[14].

Another limitation is that GI was used as the principal global descriptor of dose fall-off. Although GI is widely used

in SBRT plan assessment, it does not characterize local or directional gradients toward individual OARs. Future studies should incorporate additional spatial dose-gradient metrics such as D2cm, gradient distance, shell-based dose fall-off analysis, or directional gradient evaluation around the PTV. These metrics may provide a more detailed understanding of how delivery geometry and beam modulation influence clinically relevant dose fall-off in different anatomical scenarios.

The NC-VMAT configurations used in this study should also be interpreted within a methodological context. Couch rotations of 45°, 60°, 75°, and 90° were included to evaluate geometric sensitivity under controlled planning conditions. However, extensive couch rotations are not always feasible in routine clinical practice because of collision risk, gantry clearance, immobilization limitations, and increased setup complexity. Therefore, the present results should not be interpreted as a direct recommendation to use all evaluated non-coplanar configurations clinically.

Overall, this study indicates that all evaluated delivery techniques can achieve acceptable lung SBRT plans under standardized planning conditions. VMAT-based techniques provided a clear advantage in planned beam-on delivery time, whereas HT-based techniques, particularly DB-HT, showed lower mean values for selected lung and mediastinal OAR parameters. However, because of the limited cohort size and absence of anatomical subgroup analysis, these findings should be interpreted as planning observations rather than definitive evidence of clinical superiority. Larger studies incorporating central and peripheral lesions, formal PTV-OAR distance stratification, and additional directional or shell-based gradient metrics are needed to clarify the conditions under which specific delivery techniques provide clinically meaningful advantages.

Conclusions

Under the standardized planning conditions used in this study, all evaluated techniques achieved clinically acceptable target coverage. Although statistically significant overall differences were observed for selected parameters, including PTV V50 coverage, GI, HI, lung V20, mean lung dose, heart D0.1cc, and aorta D0.1cc, the clinical interpretation of these findings should remain cautious because of the limited sample size and the absence of formal anatomical subgroup analysis.

The clearest technique-related difference was planned beam-on delivery time, which was substantially shorter for VMAT-based techniques than for HT-based techniques. HT-based plans, particularly DB-HT, showed lower mean values for selected lung and mediastinal OAR dose parameters; however, these findings should be interpreted as descriptive because no corrected pairwise post-hoc comparison or anatomical subgroup analysis was performed. These findings suggest that delivery technique and beam modulation strategy may influence specific dosimetric endpoints, but they do not establish a general clinical superiority of one technique over another.

Overall, the results support a combined evaluation of target coverage, plan-quality indices, OAR dose parameters, and treatment delivery efficiency when comparing lung SBRT planning techniques. Larger studies including both peripheral and central lesions, formal PTV-OAR distance stratification, and additional spatial or directional dose-gradient metrics are needed to determine whether the observed dosimetric differences translate into consistent clinical advantages.

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