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Optimization of Whole-Breast Irradiation: A Dosimetric Comparison of 3D-CRT, IMRT, and VMAT in Left-Sided Breast Cancer

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Abstract

Objective

To compare the dosimetric performance and planning efficiency of three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT), and volumetric-modulated arc therapy (VMAT) for whole-breast irradiation in left-sided breast cancer.

Methods

Twenty patients with left-sided breast cancer (stage I–IIA, pT1-2N0M0) were included. For each patient, 3D-CRT, IMRT, and VMAT treatment plans were generated and optimized. Parameters assessed included target conformity and homogeneity indices; organ-at-risk doses (heart, lungs, and spinal cord) and planning efficiency.

Results

VMAT demonstrated superior target conformity and dose homogeneity compared with both 3D-CRT and IMRT ($p < 0.001$ for both). Compared with 3D-CRT, VMAT reduced cardiac high-dose exposure and ipsilateral lung V40. However, VMAT increased the maximum spinal cord dose and contralateral lung V5. Although 3D-CRT provided superior spinal cord sparing and avoided contralateral lung low-dose exposure but exhibited inferior target conformity. IMRT achieved comparable target coverage to VMAT but with lower planning efficiency.

Conclusion

VMAT is advantageous in target dose conformity, homogeneity, cardiac sparing, and delivery efficiency, supporting its use as a preferred technique for left-sided breast radiotherapy. Individualized optimization should be considered to mitigate low-dose contralateral lung and spinal cord exposure based on patient-specific anatomy.

1. Background

Breast cancer remains the most common malignancy among women worldwide. With widespread screening and advances in early detection, approximately 60% of newly diagnosed cases are identified at stages I–IIA [1–3]. Breast-conserving surgery followed by adjuvant radiotherapy is the standard of care for these patients [4–6].

Radiotherapy techniques have evolved from two-dimensional approaches to three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT), and volumetric modulated

arc therapy (VMAT), improving dose delivery precision and target coverage [7, 8]. However, considerable debate remains regarding their dosimetric performance and clinical applicability. 3D-CRT is simple and limits low-dose irradiation of surrounding tissues but has limited dose modulation capacity in complex treatment regions.

IMRT improves dose conformity and target coverage but may increase low-dose cardiac exposure. VMAT combines superior conformity, efficient dose modulation, and improved normal tissue sparing through rotational beam delivery and dynamic multileaf collimator (MLC) movement [7–10]. However, concerns persist regarding increased spinal cord dose, greater low-dose peripheral tissue exposure, and higher implementation costs, which may limit accessibility [11–13].

Dosimetric comparisons, particularly regarding cardiac exposure in left-sided breast cancer, a factor associated with radiation-induced coronary injury, have yielded inconsistent results [9, 10]. Some investigations have reported superior normal tissue sparing with VMAT [11, 12], whereas others have found 3D-CRT or IMRT to provide comparable or better protection against low-dose irradiation of adjacent organs [13–15]. Published studies have primarily focused on target coverage and cardiac sparing, with limited attention to spinal cord dose, contralateral lung exposure (including V5), and planning efficiency. No consensus has been established regarding the optimal technique for whole-breast irradiation [7, 8, 16].

The present study provides a comprehensive dosimetric comparison of 3D-CRT, IMRT, and VMAT plans generated for each patient. Parameters included target conformity index (CI), homogeneity index (HI), cardiac dose metrics (V5–V40 and left anterior descending artery [LAD] dose), pulmonary parameters (ipsilateral lung V20–V40 and contralateral lung V5), spinal cord dose, and planning efficiency indicators such as monitor units and treatment delivery time. The study aimed to characterize VMAT limitations regarding spinal cord and contralateral lung sparing and its advantages in cardiac and coronary artery dose reduction, providing evidence for individualized treatment selection.

2. Methods

2.1. Patient selection

Twenty patients with left-sided breast cancer (stage I-IIA pT1-2N0M0) who underwent breast-conserving surgery between January 2023 and December 2024 were included. Patients were aged 18–75 years, had pathologically confirmed invasive ductal carcinoma, and had no history of prior thoracic radiotherapy. Patients with severe cardiopulmonary disease or metallic implants that could interfere with dose calculation were excluded.

All simulation CT datasets were anonymized before analysis. For each patient, 3D-CRT, FFIO-IMRT, and VMAT treatment plans were generated for research purposes. The study protocol was approved by the institutional ethics committee (No. KY-2025-114-01).

2.2. Radiotherapy preparation

Patients were positioned supine on a breast board with both arms elevated and were immobilized using a thermoplastic mask. Simulation CT was performed using a large-bore CT scanner (Siemens Somatom Confidence RT Pro) with the following acquisition parameters: 120 kV tube voltage, 3 mm slice thickness, and a 512 × 512 image matrix. Images were imported into the treatment planning system for contouring and plan generation.

Target volume delineation was performed by two senior radiation oncologists. The clinical target volume (CTV) comprised the ipsilateral breast tissue cropped 5 mm from the skin surface. The planning target volume (PTV) was generated by applying a 5-mm expansion to the CTV and retracting 3 mm from the skin surface.

2.3. Radiotherapy planning

For each patient, three treatment plans (3D-CRT, FFIO-IMRT, and VMAT) were generated and optimized using 6 MV X-rays, with a prescribed dose of 50 Gy delivered to the PTV in 25 fractions.

For 3D-CRT, tangential beam arrangements at gantry angles of 45–75° (right anterior oblique) and 240°–270° (left posterior oblique) were used. FFIO-IMRT used seven equally spaced coplanar fields, optimized on a 5-mm calculation grid, with a minimum monitor unit (MU) threshold of 5 and a maximum of 100 optimization iterations. VMAT used dual full arcs in clockwise (180°–179°) and counter-clockwise (179°–180°) directions, with gantry rotation speed of 4°/s and MLC speed of 2.5 cm/s.

Optimization objectives required that at least 95% of the PTV receive 95% of the prescribed dose, while no more than 5% of the PTV received doses exceeding 110% of the prescription. Dose constraints for organs at risk (OARs) were defined in accordance with ESTRO 2023 guidelines [8], including heart V20 < 5% and mean heart dose < 4 Gy. For the ipsilateral lung, constraints included V20 < 25% and V5 < 60%.

2.4. Dosimetric parameters

2.4.1. Conformity index

CI assesses the agreement between the 95% isodose volume and the PTV, calculated as:

$$CI = (V_{tref}/V_t) \times (V_{tref}/V_{ref})$$

where V_{tref} represents the target volume covered by the 95% isodose, V_t is the total target volume, and V_{ref} is the total volume covered by the 95% isodose. CI values range from 0 to 1, with higher values indicating greater conformity [17].

2.4.2. Homogeneity index

Dose uniformity within the PTV was assessed using the HI.

$HI = (D_2 - D_{98}) / D_{50}$

where D_2 and D_{98} are the doses received by 2% and 98% of the PTV, respectively, and D_{50} is the median dose. Lower HI indicates greater dose homogeneity.

2.4.3. OAR parameters

Dosimetric evaluation of organs at risk included the following metrics:

Heart: V5, V20, V30, V40, mean dose (Dmean), and maximum dose (Dmax), as well as Dmax for the left anterior descending artery.

Lungs: Ipsilateral lung V5, V20, V30, V40, and Dmean; contralateral lung V5 and Dmean;

Spinal cord: Dmax.

Volume parameters (Vx) were defined as the percentage of organ volume receiving at least x Gy. Dose parameters were reported as Dmean and Dmax.

2.4.4. Planning efficiency parameters

Planning efficiency was assessed by total monitor units (MUs) and beam delivery time (seconds).

2.5. Statistical analysis

Statistical analyses were performed using R software (version 4.2.2) [18]. In this three-arm paired design, pairwise within-patient differences were calculated for three comparisons: IMRT-minus-3D-CRT, VMAT-minus-3D-CRT, and VMAT-minus-IMRT.

Continuous variables were presented as mean (standard deviation) and compared using paired t-tests, whereas categorical variables were presented as frequency and percentages [19]. A two-sided p-value < 0.05 was considered statistically significant.

Box plots illustrated PTV coverage and planning efficiency parameters. Forest plots depicted standardized mean differences (SMD) for heterogeneous OAR dosimetric outcomes.

3. Results

3.1. Patient and plan characteristics

Twenty patients with left-sided breast cancer (stage I-IIA, pT1-2N0M0) who underwent lumpectomy were included. For each patient, 3D-CRT, IMRT, and VMAT plans were generated. Baseline planning parameters are summarized in Table 1.

Table 1
Baseline dosimetric parameters of the three radiotherapy plans

Characteristic	CRT N = 20[1]	IMRT N = 20[1]	VMAT N = 20[1]
CI	0.62 (0.58, 0.67)	0.81 (0.78, 0.84)	0.88 (0.86, 0.89)
HI	0.11 (0.11, 0.13)	0.12 (0.08, 0.16)	0.08 (0.08, 0.09)
Spine_Dmax	49 (45, 54)	111 (101, 117)	446 (381, 582)
Left_lung_V5	33 (27, 36)	43 (37, 46)	46 (39, 52)
Left_lung_V20	21.6 (16.4, 24.2)	17.4 (15.5, 19.9)	13.0 (10.5, 15.6)
Left_lung_V30	18.4 (13.6, 19.7)	12.2 (10.0, 14.7)	7.3 (5.8, 9.2)
Left_lung_V40	14.8 (10.5, 16.1)	7.9 (5.8, 9.2)	3.0 (1.2, 3.8)
Left_lung_Dmean	1,128 (888, 1,243)	1,056 (919, 1,167)	896 (788, 1,005)
Right_lung_V5	0 (0, 0)	1 (0, 3)	20 (10, 24)
Right_lung_Dmean	43 (40, 52)	119 (108, 138)	363 (304, 381)
Heart_V5	21 (19, 28)	32 (23, 36)	33 (24, 40)
Heart_V20	13.7 (10.7, 19.1)	5.5 (3.6, 8.7)	3.8 (2.9, 5.3)
Heart_V30	11.4 (8.4, 15.1)	2.8 (1.8, 4.8)	1.5 (0.6, 2.0)
Heart_V40	8.8 (6.5, 11.5)	1.1 (0.5, 2.6)	0.2 (0.0, 0.5)
Heart_Dmean	736 (637, 951)	565 (465, 656)	562 (493, 630)
Heart_Dmax	5,260 (5,215, 5,311)	5,106 (4,831, 5,188)	4,682 (4,320, 4,911)
LAD_Dmax	5,186 (5,095, 5,242)	4,572 (3,949, 4,968)	3,944 (3,305, 4,246)
Mus	375 (335, 463)	576 (514, 600)	720 (663, 757)
out_time	37 (33, 46)	154 (146, 164)	108 (104, 120)

[1]Median (Q1, Q3)

VMAT demonstrated superior target conformity (CI = 0.88 ± 0.03) and improved dose homogeneity (HI = 0.08 ± 0.02) with significant cardiac and high-dose OAR sparing, and a marked reduction in left lung V40 compared with 3D-CRT (3.0 ± 1.8% vs. 14.8 ± 4.7%), corresponding to a 79.7% decrease.

In contrast, 3D-CRT achieved the lowest spinal cord dose (49 ± 8 cGy) and avoided low-dose exposure to the contralateral lung (V5 = 0%), but had the least favorable target conformity (CI = 0.62 ± 0.06).

3.2. Target parameters comparison

Target dosimetric parameters are presented in Table 2. With respect to the CI, the VMAT-CRT difference was greater than both the IMRT-CRT (0.18 ± 0.08) and VMAT-IMRT (0.07 ± 0.03) comparisons, reflecting improved conformity with VMAT.

Table 2
Paired comparison of planning parameter differences among the three radiotherapy techniques

Characteristic	IMRT-CRT		VMAT-CRT		VMAT-IMRT	
	N = 20[1]	p-value[2]	N = 20[1]	p-value[2]	N = 20[1]	p-value[2]
CI	0.20 (0.11, 0.26)	**< 0.001**	0.26 (0.20, 0.31)	**< 0.001**	0.08 (0.04, 0.09)	**< 0.001**
HI	-0.01 (-0.03, 0.04)	0.8	-0.03 (-0.05, -0.01)	**< 0.001**	-0.03 (-0.07, 0.00)	**0.001**
1Median (Q1, Q3)						
2Wilcoxon signed rank test with continuity correction; Wilcoxon signed rank exact test						

For the HI, VMAT demonstrated lower values relative to both CRT and IMRT, as indicated by negative differences for VMAT–CRT (-0.040 ± 0.052) and VMAT–IMRT (-0.041 ± 0.045), supporting superior dose homogeneity. No statistically significant difference in HI was observed between IMRT and CRT ($p = 0.8$). Parameter distributions are illustrated in Fig. 1.

3.3. Comparison of OAR dose parameters

OAR dose differences among the three techniques are presented in Table 3. The maximum dose to the spinal cord increased with IMRT (+ 60 cGy compared with CRT) and markedly higher with VMAT (+ 451 cGy vs. CRT; +391 cGy vs. IMRT), indicating inferior spinal cord protection with IMRT and VMAT relative to 3D-CRT.

Table 3
Paired comparison of organ-at-risk (OAR) dose parameter differences among the three radiotherapy techniques

Characteristic	IMRT-CRT		VMAT-CRT		VMAT-IMRT	
	N = 20[1]	p-value[2]	N = 20[1]	p-value[2]	N = 20[1]	p-value[2]
Spine_Dmax	60 (52, 66)	**< 0.001**	394 (332, 530)	**< 0.001**	330 (271, 474)	**< 0.001**
Left_lung_V5	9 (6, 13)	**< 0.001**	15 (9, 20)	**< 0.001**	5 (0, 10)	0.070
Left_lung_V20	-3.2 (-6.4, -0.7)	**0.004**	-8.8 (-10.2, -4.6)	**< 0.001**	-4.0 (-5.6, -3.1)	**< 0.001**
Left_lung_V30	-5.8 (-8.3, -2.3)	**< 0.001**	-10.7 (-11.9, -7.7)	**< 0.001**	-4.0 (-6.1, -2.7)	**< 0.001**
Left_lung_V40	-6.6 (-8.5, -3.3)	**< 0.001**	-11.2 (-12.8, -8.6)	**< 0.001**	-4.5 (-6.4, -2.9)	**< 0.001**
Left_lung_Dmean	-96 (-211, 19)	0.14	-200 (-335, 7)	**0.004**	-97 (-191, -27)	**0.011**
Right_lung_V5	1 (0, 3)	**0.001**	20 (10, 24)	**< 0.001**	18 (10, 23)	**< 0.001**
Right_lung_Dmean	70 (55, 93)	**< 0.001**	300 (260, 331)	**< 0.001**	214 (177, 255)	**< 0.001**
Heart_V5	8 (1, 15)	**0.001**	8 (2, 17)	**< 0.001**	1 (-4, 9)	0.5
Heart_V20	-7 (-11, -5)	**< 0.001**	-9 (-13, -7)	**< 0.001**	-2 (-3, 0)	**0.027**
Heart_V30	-7.8 (-11.2, -5.8)	**< 0.001**	-10.0 (-12.8, -7.4)	**< 0.001**	-0.9 (-2.6, -0.4)	**< 0.001**
Heart_V40	-7.2 (-10.1, -5.5)	**< 0.001**	-8.6 (-11.2, -6.1)	**< 0.001**	-1.0 (-2.1, -0.3)	**< 0.001**
Heart_Dmean	-153 (-358, -73)	**< 0.001**	-214 (-383, -62)	**< 0.001**	5 (-83, 77)	0.8
Heart_Dmax	-141 (-413, -31)	**0.002**	-569 (-972, -344)	**< 0.001**	-413 (-502, -224)	**< 0.001**
LAD_Dmax	-667 (-1,175, -248)	**< 0.001**	-1,316 (-1,835, -918)	**< 0.001**	-571 (-867, -241)	**< 0.001**
Mus	166 (116, 258)	**< 0.001**	317 (250, 395)	**< 0.001**	153 (73, 194)	**< 0.001**

1Median (Q1, Q3)

2Wilcoxon signed rank test with continuity correction; Wilcoxon signed rank exact test

For lung dosimetry, VMAT was associated with a small increase in ipsilateral lung V5 compared with IMRT (+ 4%). VMAT provided the greatest reduction in ipsilateral lung intermediate-to-high-dose exposure, with decreases in V20–V40 and Dmean (-162 cGy vs. CRT). Contralateral lung V5 increased modestly with IMRT versus 3D-CRT (+ 1.35%) and further with VMAT comparisons (VMAT vs. CRT: +18%; VMAT vs. IMRT: +17%).

In terms of cardiac exposure, both IMRT and VMAT demonstrated improved protection compared with CRT, as evidenced by reductions in V20 (IMRT vs. CRT: −12.8%; VMAT vs. CRT: −14.7%), alongside significant decreases in V20–V40 and mean dose (− 208 cGy and − 225 cGy, respectively; $p < 0.001$). VMAT also achieved the greatest reduction in left anterior descending artery maximum dose (-1,316 cGy; $p < 0.001$).

Overall, VMAT provided optimal cardiac and ipsilateral lung sparing at high-dose levels, whereas 3D-CRT and IMRT offered relatively better contralateral lung and low-dose protection. Spinal cord dose requires further optimization across all techniques. SMD distributions for OARs are presented in Fig. 2.

3.4. Planning efficiency parameters

Planning efficiency results are summarized in Table 4. Compared with 3D-CRT, IMRT and VMAT required significantly more MUs (IMRT: 166; VMAT: 317) and longer delivery times (IMRT: 112 seconds; VMAT: 71 seconds), with all differences reaching statistical significance (both $p < 0.001$).

Table 4
Paired comparison of planning efficiency parameter differences among the three radiotherapy techniques.

Characteristic	IMRT-CRT		VMAT-CRT		VMAT-IMRT	
	N = 20[1]	p-value[2]	N = 20[1]	p-value[2]	N = 20[1]	p-value[2]
Mus	166 (116, 258)	**< 0.001**	317 (250, 395)	**< 0.001**	153 (73, 194)	**< 0.001**
Delivery time(s)	112 (106, 125)	**< 0.001**	71 (61, 82)	**< 0.001**	-42 (-55, -36)	**< 0.001**
1Median (Q1, Q3)						
2Wilcoxon signed rank test with continuity correction; Wilcoxon signed rank exact test						

VMAT required more Mus than IMRT (increase of 153; $p < 0.001$), but achieved a shorter delivery time (decrease of 42 seconds; $p < 0.001$). IMRT and VMAT showed greater plan complexity and reduced efficiency compared to 3D-CRT. Despite higher complexity compared with IMRT, VMAT improved delivery efficiency by shortening treatment time. Parameter differences are illustrated in Fig. 3.

4. Discussion

Radiotherapy for breast cancer aims to improve target dose conformity while reducing radiation exposure to normal tissues. The three principal techniques in contemporary clinical practice are: 3D-CRT, IMRT, and VMAT [7].

3D-CRT uses coplanar beams to achieve basic geometric conformity. It is simple, broadly accessible, and produces relatively limited low-dose exposure compared with IMRT. However, dose conformity in anatomically complex regions remains restricted [14, 20–22]. IMRT improves 3D dose modulation through MLC-based beam shaping, thereby enhancing target conformity but may increase low-dose cardiac exposure (e.g., V5), despite reducing higher-dose parameters such as V30 when compared with 3D-CRT [23]. VMAT enables full-arc irradiation in approximately 2.5–4.0 minutes through synchronized gantry rotation and dynamic MLC movement. This technique has been associated with a reduction in the left anterior descending artery maximum dose of approximately 15 Gy, but may increase low-dose cardiac exposure V5 by approximately 18% [20].

Whether the broader low-dose distribution of VMAT increases the risk of late cardiac toxicity and secondary malignancies remains debated [15, 20, 24, 25]. It is also uncertain whether the shorter delivery time offsets the higher MU requirements, which may increase machine wear and setup uncertainties [26].

These unresolved issues highlight the continued need for detailed dosimetric evaluation in left-sided breast cancer radiotherapy.

Our dosimetric analysis demonstrated distinct advantages and limitations for each techniques. VMAT demonstrated superior target conformity (CI = 0.88 ± 0.03) and dose homogeneity (HI = 0.08 ± 0.02) compared with both IMRT and CRT ($p < 0.001$ for all comparisons), consistent with Boyages et al., who reported that arc-based optimization may overcome certain limitations of conventional IMRT [7].

VMAT also demonstrated superior cardiac sparing, with a marked reduction in left anterior descending artery maximum dose (3,944 ± 733 cGy vs. 5,186 ± 140 cGy with CRT), corresponding to a mean decrease of 1,396 ± 683 cGy. These findings are consistent with prior evidence of improved high-dose cardiac sparing with VMAT techniques [20].

However, VMAT was associated with a significantly higher spinal cord maximum dose (446 ± 168 cGy vs. CRT: 49 ± 8 cGy) and reduced contralateral lung protection, reflected by higher V5 exposure (20 ± 7% vs. CRT: 0%) consistent with known concerns about peripheral low-dose irradiation with rotational delivery [14].

In contrast, CRT provided optimal spinal cord protection and eliminated low-dose exposure to the contralateral lung; however, its suboptimal target conformity (CI = 0.62 ± 0.06) and limited high-dose cardiac control, which may restrict its applicability in precision radiotherapy. IMRT improved conformity over CRT (CI = 0.81 ± 0.05) but required longer delivery (154 ± 14 seconds) with higher cardiac V20 (5.5 ±

4.5%) and greater coronary artery doses (4,572 ± 727 cGy) compared with VMAT, indicating comparatively reduced efficiency and less favorable OAR sparing.

Several methodological limitations should be acknowledged. The single-center design and small sample size limit generalizability. Cardiac substructure irradiation was not comprehensively evaluated, despite its recognized importance in estimating the risk of long-term radiation-induced cardiac toxicity. Multicenter studies incorporating advanced cardiac imaging and dose-response modeling are therefore warranted [27, 28].

Further refinement of planning algorithms is needed to reduce VMAT-associated spinal cord and contralateral lung low-dose exposure while preserving its dosimetric benefits. Integration of VMAT with deep inspiration breath hold also warrants investigation.

5. Conclusion

Although further optimization is needed to improve spinal cord sparing and reduce low-dose exposure to the contralateral lung, VMAT demonstrated the most favorable overall balance of target coverage, cardiac sparing, and delivery efficiency. These dosimetric advantages support its use as the preferred radiotherapy technique for patients with left-sided breast cancer.

Abbreviations

3D-CRT
Three-dimensional conformal radiotherapy
IMRT
Intensity-modulated radiotherapy
VMAT
Volumetric-modulated arc therapy
FFIO-IMRT
Fixed Field Inversely Optimized Intensity-Modulated Radiation Therapy
MLC
Multileaf collimator
CTV
Clinical target volume
PTV
Planning target volume
OAR
Organ at risk
CI
Conformity index
HI

Homogeneity index
MU
Monitor unit
LAD
Left anterior descending artery
DIBH
Deep inspiration breath hold
ESTRO
European Society for Radiotherapy and Oncology
MLC
Multileaf collimator
TPS
Treatment planning system
Dmean
Mean dose
Dmax
Maximum dose
Vx
Volume receiving ≥ x Gy
SMD
Standardized mean difference

Declarations

Ethics approval and consent to participate

Ethics approval: This study was approved by the Ethics Committee of the Affiliated Huaian No. 1 People's Hospital of Nanjing Medical University (No. KY-2025-114-01).

Consent to participate

and publish: Due to the retrospective nature of the study, informed consent was waived.

Consent for publication

Not applicable.

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Competing interests

The authors declare that they have no competing interests.

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Author Contribution

Bo-Ya Zheng: Conceptualization, Data curation, Formal Analysis, Writing – original draft.Ya-Qi Song: Data curation, Formal Analysis, Writing – original draft.Yi Ren: Data curation, Writing – original draft, Writing – review & editing.Min-Min Liu: Data curation, Writing – review & editing.Ji-Hua Han: Formal Analysis, Writing – review & editing.Hua Liu: Conceptualization, Formal Analysis, Writing – review & editing.Hong-Lei Luo: Conceptualization, Formal Analysis, Writing – review & editing.All authors read and approved the final manuscript.

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Data Availability

Any researchers interested in this study could contact us for requiring the data.

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Figures

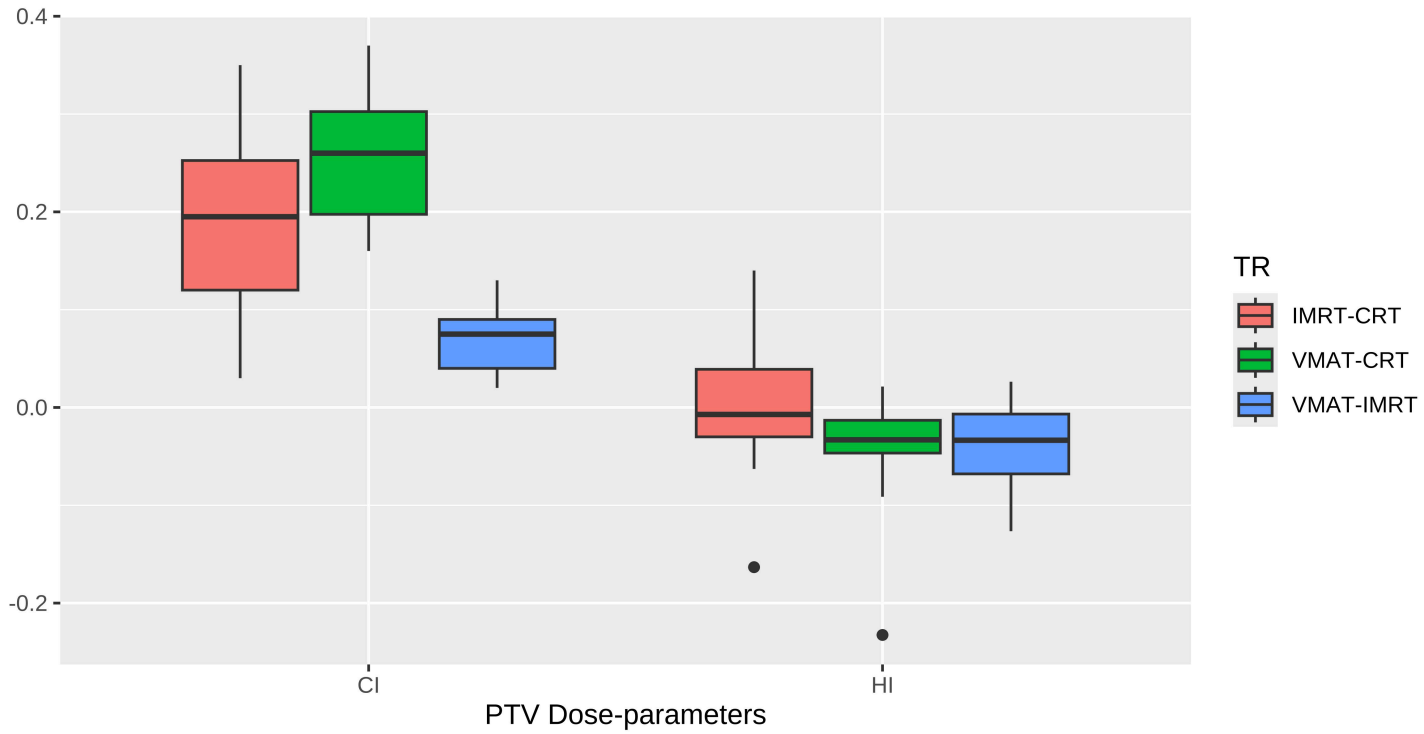


Figure 1

Distribution of CI and HI differences among the three radiotherapy techniques.

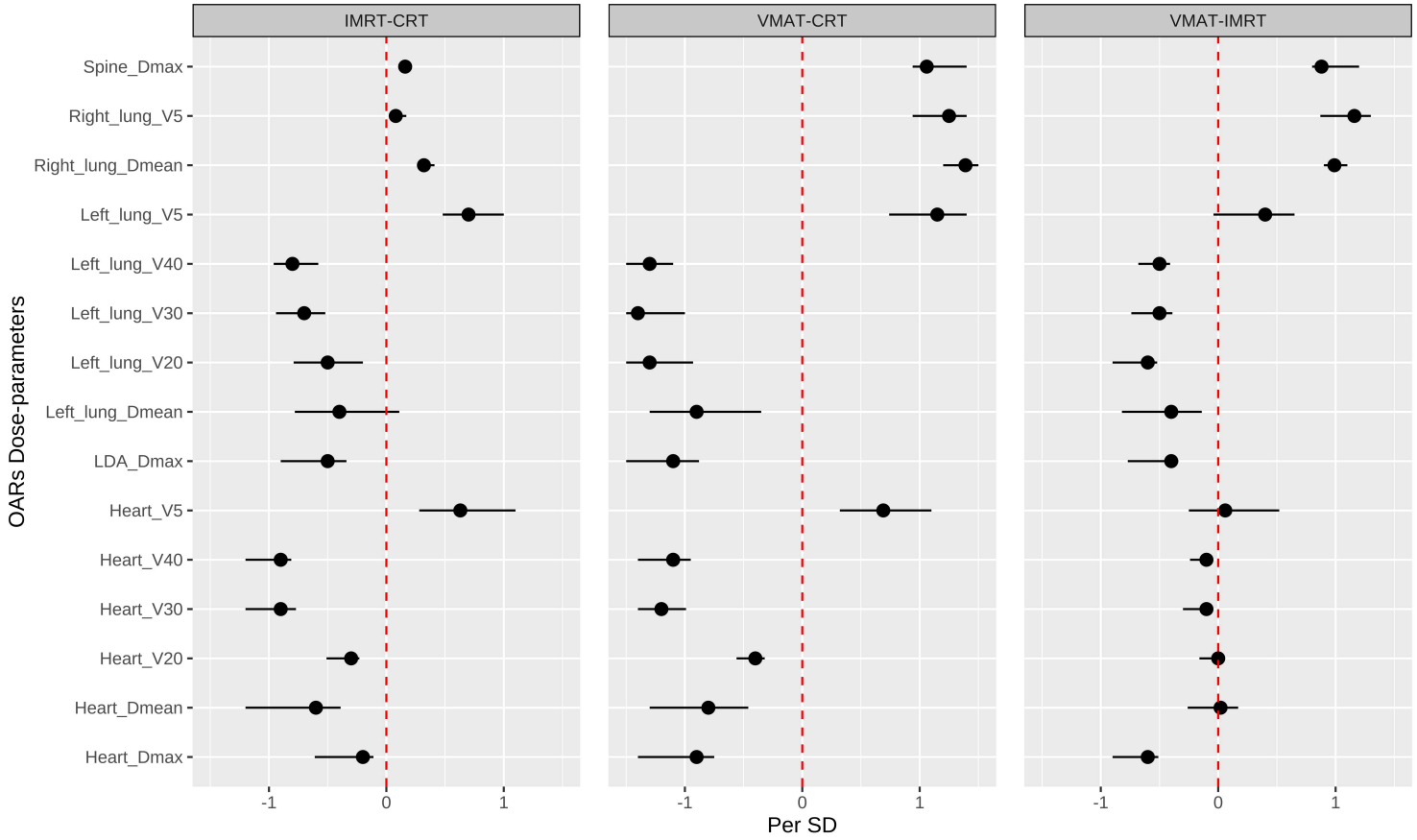


Figure 2

Forest plot of OAR dose parameter differences among the three-radiotherapy technique comparisons (IMRT-CRT, VMAT-CRT, and VMAT-IMRT).
The x-axis represents standardized mean differences, with each unit corresponding to one standard deviation, while the y-axis lists OAR dosimetric parameters, including spinal cord maximum dose (Dmax), cardiac parameters (V5, V20, V30, V40, Dmean, and Dmax), bilateral lung parameters (V5, V20, V30, V40, and Dmean), and left anterior descending artery (LAD) Dmax. Data are presented as mean ± standard deviation. Negative values (leftward shift) indicate dose reduction and therefore represent a dosimetric advantage, whereas positive values (rightward shift) indicate increased dose and a potential disadvantage. Each subplot represents a pairwise comparison; for example, IMRT-CRT denotes the difference between IMRT and CRT. Smaller absolute standardized mean differences indicate superior OAR sparing.

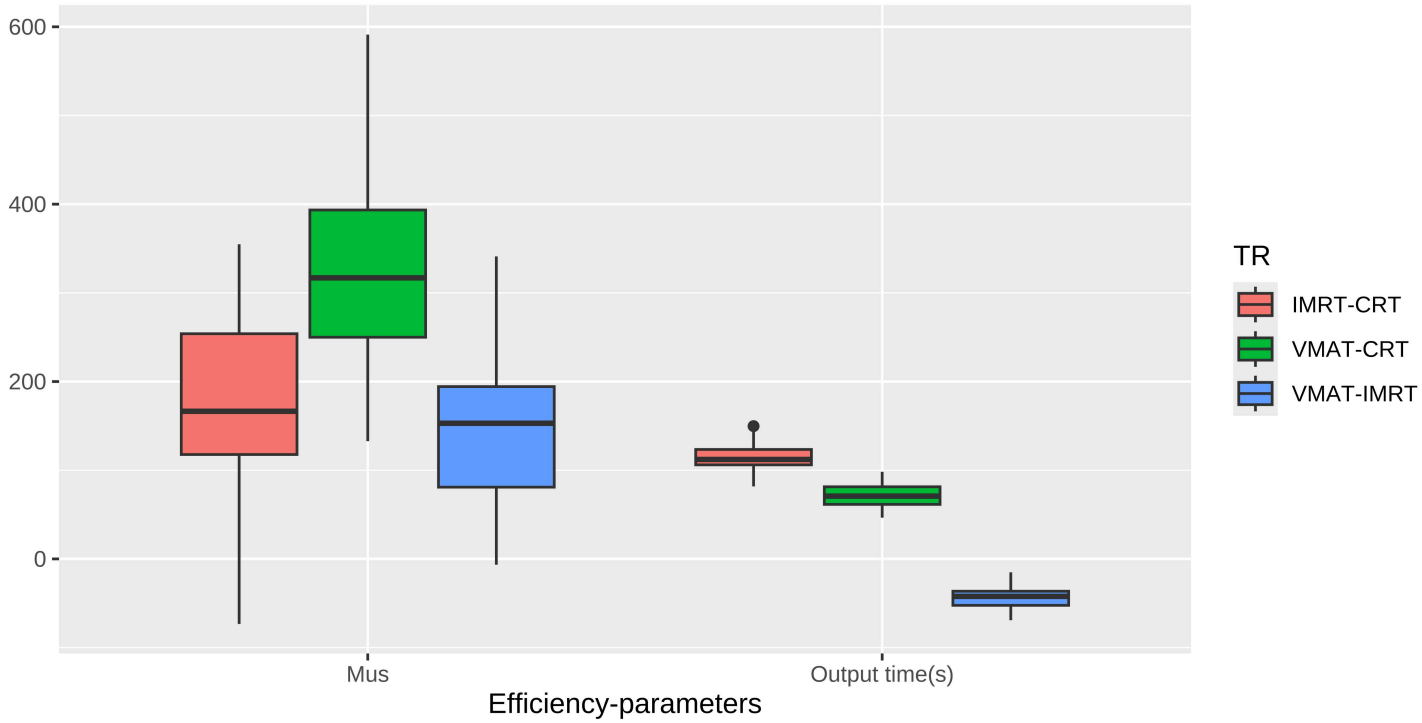


Figure 3

Distribution of MUs and treatment delivery time (seconds) among the three radiotherapy techniques.