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Examination of the dose distribution of volumetric modulated arc radiotherapy using a high-definition multi-leaf collimator for breast cancer patients with irradiated regional lymph nodes

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ABSTRACT

Background: A high-definition multi-leaf collimator (HD-MLC) with 5- and 10-mm fine MLCs is useful for radiotherapy. However, it is difficult to irradiate the mammary gland and supraclavicular region using a HD-MLC because of the narrow field of volumetric modulated arc radiotherapy (VMAT). Therefore, we aimed to evaluate the dose distribution of the VMAT dose using a HD-MLC in 15 patients with left breast cancer undergoing postoperative irradiation of breast and regional lymph nodes, including the internal mammary node.

Materials and methods: The following four plans were generated: three-arc VMAT using HD-MLC (HD-VMAT), two tangential arcs and one-arc VMAT using HD-MLC (tHD-VMAT), three-dimensional conformal radiotherapy (3DCRT) using HD-MLC, and two-arc VMAT using the Millennium 120-leaf MLC (M-VMAT). We assessed the doses to the target volume and organs at risk.

Results: The target dose distributions were higher for HD-VMAT than 3DCRT. There were no significant differences in the heart mean dose (D_{mean}) or lung volume receiving 20 Gy (V20 Gy) between HD-VMAT and 3DCRT. The heart D_{mean} and lung V20 Gy of tHD-VMAT were higher than those of HD-VMAT, and the heart D_{mean} of M-VMAT was higher than that of HD-VMAT. However, the target doses of tHD-VMAT, M-VMAT, and HD-VMAT were equivalent.

Conclusions: In cases of the mammary gland and regional lymph node irradiation, including the internal mammary node in patients with left breast cancer, HD-VMAT was not inferior to M-VMAT and provided a better dose distribution to the target volume and organs at risk compared with 3DCRT and tHD-VMAT.

Key words: breast cancer; volumetric modulated arc therapy; high-definition multi-leaf collimator; Millennium 120-leaf MLC; three-dimensional conformal radiotherapy

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Introduction

Radiotherapy is usually considered after breast-conserving surgery, as it increases local control and breast cancer patients survival [1, 2]. Moreover, irradiation of regional nodes, including the supraclavicular and internal mammary nodes (IMNs), and the whole breast is recommended to improve disease-free survival (DFS) and distant DFS in high-risk patients with breast cancer [3, 4]. The National Comprehensive Cancer Network guidelines recommend irradiating the regional lymph nodes and the mammary gland during breast-conserving therapy for patients with invasive cancer and more than one lymph node metastasis and for high-risk patients requiring mastectomy [5]. Generally, the supraclavicular region is irradiated with the whole breast and its regional lymph nodes. In contrast, there is an inconsistency in the irradiation of internal mammary nodes between institutions, primarily due to cardiac and lung toxicity. However, in high-risk patients, irradiation of the IMN recently demonstrated lower rates of breast cancer mortality and distant recurrence compared with no IMN irradiation [6, 7]. Irradiation methods that include the IMN are three-dimensional conformal radiotherapy (3DCRT), volumetric modulated arc radiotherapy (VMAT), particle beams, and a combination of electron beams and X-rays [8, 9]. A linear accelerator with a maximum irradiation field size of 40 cm using a multi-leaf collimator (MLC) is generally used. However, there have been no studies on dose distributions using a high-definition multi-leaf collimator (HD-MLC) with a maximum irradiation field of 22 × 28.6 cm^2 during VMAT irradiation because the field size is limited. Therefore, it is unclear whether VMAT using HD-MLC is appropriate in the case of irradiating a large area, such as the breast and supraclavicular area. This study aimed to evaluate the dose distribution of VMAT, using HD-MLC, for left breast cancer patients who underwent whole breast and regional nodes adjuvant radiotherapy.

Materials and methods

Patients

This retrospective study included 15 consecutive patients [median age, 48 (39–77) years] who underwent locoregional irradiation after left breast surgery (lumpectomy or mastectomy with immediate breast reconstruction) and axillary lymphadenectomy between September 2014 and February 2018. This was an observational study in which computed tomography (CT) (Toshiba Aquilion LB; Toshiba Medical, Otawara, Japan) images of the patients were used to create a treatment plan. Nine patients underwent breast conservative surgery, and six underwent breast reconstruction. The patients underwent CT while free breathing in the supine position, with both arms raised. A vacuum pillow was used to fix their heads and arms. The study was approved by the institutional review board for clinical research at Tokai University (18R126).

Contouring

A medical physicist delineated contours that were confirmed or revised by a radiation oncologist according to the RTOG Breast Cancer Atlas [10]. Subsequently, the left side of the whole breast was delineated and cropped 5 mm to the skin contour and designated as the breast clinical target volume (CTV) [11]. Regional lymph nodes including the IMN were labeled as prophylactic CTV, and the breast CTV and prophylactic CTV together were designated as the CTV. The planning target volume (PTV) was created by adding a 5-mm margin to the CTV in all directions. The PTV of the IMN (PTV_IM) was generated by adding a 5-mm margin to the IMN in all directions. For optimization and normalization purposes, PTV for optimization (OP_PTV) was generated by a 3-mm margin from the skin surface and was excluded from the PTV. The organs at risk (OARs) defined in this study included the heart (from the inferior to pulmonary artery to the apex of the heart), lungs (contralateral and ipsilateral lungs), and contralateral breast. The CTV, PTV, lung and heart volumes, and head-to-caudal length of the PTV of the 15 patients are presented in Table S1.

Planning

Four plans were generated: (1) three-arc VMAT using the Novalis TX system (Varian Medical Systems, Palo Alto, CA, USA) equipped with HD-MLC (HD-VMAT), (2) two tangential arcs and one-arc VMAT using the Novalis TX equipped with HD-MLC (tHD-VMAT), (3) 3DCRT using the Novalis TX equipped with

HD-MLC, and (4) two-arc VMAT using the Clinac 21EX (Varian Medical System) equipped with the Millennium 120-leaf MLC (M-VMAT; maximum jaw size, 40 × 40 cm^2). For 3DCRT, the caudal border of the humeral head was used as the reference; the cranial side was irradiated with the lymph node region, and the caudal side was irradiated with the breast. The edges of the irradiation field on the cranial and caudal sides were aligned parallel to each other, and tangential irradiation was performed. The gantry angle for tangential irradiation was chosen to avoid irradiating the lungs as much as possible (Supplementary File — Fig. S1A).

The planning method for the HD-VMAT treatment plan is shown in Supplementary File — Figure S1B. For HD-VMAT, the cranial side comprised one arc (−40° to 179°), and the caudal side comprised two arcs (160° to −80° and −80° to 160°) using a single isocenter. The collimator angles of each field were adjusted to include as much of the target volume as possible within the irradiation field and were set to overlap in the cranial and caudal irradiation fields.

For tHD-VMAT, the non-irradiated area was set appropriately at the caudal side (e.g., −10° to 90°), as described by Viren et al. [12] The gantry angles and isocenter were the same as those used for HD-VMAT (Supplementary File — Fig. S1C). M-VMAT comprised two arcs using the Millennium 120-leaf MLC. A single isocenter was used, and the field size was set to include sufficient coverage from the cranial to caudal regions. The gantry angles were the same as those used for HD-VMAT (Supplementary File — Fig. S1D). The prescription dose was 50 Gy in 25 fractions.

The plans, excluding 3DCRT, were normalized to deliver the prescription dose to 50% of the OP_PTV (D50% = 50 Gy). The 3DCRT plans were normalized to the dose reference point, and the location was adjusted such that 50% of the OP_PTV was 50 ± 1 Gy. The maximum doses of all plans were adjusted to ensure that D1% of the OP_PTV was < 110% of the prescribed dose. In 3DCRT, sub-fields are used to achieve the constraint. A radiotherapy treatment planning system (Eclipse version 10.0 and 13.7; Varian Medical Systems) was used to generate all plans. Acuros XB (Varian Medical Systems) was used as the dose calculation algorithm.

All plans used 6 MV X-rays, and the calculation grid was set to 2.5 mm. The criteria for VMAT optimization were as follows: CTV D95% > 90% of the prescription dose, PTV_IM D90% > 70% (objective: 80%) of the prescription dose, D1% of the OP_PTV < 110% of the prescription dose, lung volume receiving 20 Gy (V20 Gy) < 35% (objective: 15%), lung mean dose (D_{mean}) < 20 Gy (objective: 10 Gy), heart D_{mean} < 17 Gy (objective: 7 Gy), and contralateral breast D_{mean} < 15 Gy (objective: 7 Gy).

Evaluation

The dose indices of the HD-VMAT and other plans were compared. The homogeneity index (HI), conformity index (CI), D95%, D90%, and D50% were compared between the PTVs and CTVs. HI is the ratio of the difference between the maximum (D2%) and minimum (D98%) doses to D50% (*Equation 1*):

$$HI = \frac{D2\% - D98\%}{D50\%} \times 100\ (\%) \quad (1)$$

A lower HI value indicates good uniformity within the PTV. The CI is calculated using *Equation 2*:

$$CI = \frac{VTref}{Vt} \times \frac{VTref}{Vref} \quad (2)$$

where VTref is the volume receiving the prescribed dose within the PTV, Vt is the volume of the PTV, and Vref is the total volume surrounded by the prescribed dose. The ideal CI value is 1. The OAR endpoints were V30 Gy, V20 Gy, V10 Gy, V5 Gy, and D_{mean} for the heart; V20 Gy, V10 Gy, and D_{mean} for the lungs; and V20 Gy, V10 Gy, and D_{mean} for the contralateral breast.

Statistical analyses

The two-sided Wilcoxon signed-rank test was used to determine the differences in the dose index. Statistical analysis was performed using IBM SPSS Statistics (version 26.0; IBM Corp., Armonk, NY, USA). Statistical significance was set at $p < 0.05$.

Results

Average dose–volume histograms for CTV, PTV, PTV_IM, lungs, heart, and contralateral breast are shown in Fig. S2. In comparison to tHD-VMAT,

the CTV 90% dose was significantly higher for HD-VMAT, whereas the other target doses were not significantly different between the plans. For the OARs, the lung V30 and V20 Gy and heart V30, V20, and V10 Gy, and D_{mean} were significantly lower for HD-VMAT than tHD-VMAT. Conversely, the lung V5 Gy and contralateral breast D_{mean} were significantly higher for HD-VMAT than tHD-VMAT (Fig. 1, Tab. 1 and 2). In comparison to 3DCRT, the CTV D95%, CTV D90%, PTV D95%, PTV D90%, PTV_IM D95%, and PTV_IM D90% of HD-VMAT were significantly higher. Furthermore, the HI and CI of HD-VMAT were better than those of 3DCRT. Specifically, the average PTV_IM D95% was significantly higher, by 3.61 Gy, for HD-VMAT than 3DCRT. Regarding the OARs, the lung V30 Gy and heart V30 Gy and V20 Gy were significantly lower, but the lung V10 Gy, V5 Gy, and D_{mean} and contralateral breast V10 Gy and D_{mean} were significantly higher, for HD-VMAT than 3DCRT (Fig. 1, Tab. 1 and 2). In comparison to M-VMAT, the PTV D95% and PTV D90% target doses were significantly higher for HD-VMAT. However, the HI of HD-VMAT was inferior (i.e., higher) than that of M-VMAT. Regarding the OARs, the heart D_{mean} of HD-VMAT was significantly lower, while the other target doses were not significantly different between HD-VMAT and M-VMAT (Fig. 1, Tab. 1 and 2). A representative example of the dose distribution in a large area of the heart subjected to 3DCRT and tHD-VMAT is presented in Fig. 2. Because of the use of arc fields in VMAT, the low-dose region is much broader in the left lung for HD-VMAT, tHD-VMAT, and M-VMAT than for 3DCRT.

Discussion

All target dose indices and the CI were significantly higher for HD-VMAT than 3DCRT. Meanwhile, there was no significant difference in CI between tHD-VMAT and M-VMAT compared with HD-VMAT. Moreover, although CTV D90% and PTV doses were slightly lower for tHD-VMAT and M-VMAT, respectively, the other doses were not significantly different from those of HD-VMAT. Therefore, we consider that target dose coverage was equivalent in VMAT techniques.

For PTV_IM, higher doses were obtained using HD-VMAT than 3DCRT, whereas the difference in PTV_IM among HD-VMAT, tHD-VMAT, and M-VMAT was not significant. These results suggest that HD-VMAT, tHD-VMAT, and M-VMAT, compared with 3DCRT, are the most appropriate methods for delivering different doses to the PTV_IM. Irradiation of the IMN is usually avoided in many cases to prevent exposure of the contralateral breast and heart regions to radiation. However, recently, irradiation of the IMN is being performed in high-risk patients. Luo et al. [7] evaluated IMN irradiation in a study cohort of 497 patients with clinical stage II–III breast cancer after preoperative systemic therapy and surgery. In the IMN irradiation and non-irradiation groups in their study, the 5-year DFS rates were 76.8% and 63.4%, and the 5-year overall survival (OS) rates were 88.9% and 84.1%, respectively, indicating better efficacy of IMN irradiation. Additionally, Kim et al. [13] evaluated a study cohort between 2001 and 2009, 521 patients who received neoadjuvant chemotherapy and postoperative radiotherapy for clinical stage II–III breast cancer. The 5-year DFS rates of the IMN-irradiated and non-IMN-irradiated groups were 81.8% and 72.7%, and the 5-year OS rates of IMN-irradiated and non-IMN-irradiated groups were 88.9 % and 85.5 %, respectively, indicating effective IMN irradiation. Moreover, randomized control trials have reported that IMN irradiation is effective [6, 7]. Yang et al. [14] demonstrated that among patients with an IMN ≥ 1.0 cm in size, the 5-year DFS rate was significantly higher in those treated with high-dose (63.6–70.4 Gy) compared with low-dose (50–63.5 Gy) IMN radiotherapy, although the mean difference in the average PTV_IM D95% between HD-VMAT and 3DCRT was 3.96 (–2.43 to 16.65) Gy. Therefore, HD-VMAT, tHD-VMAT, and M-VMAT were more appropriate methods for delivering a sufficient dose to PTV_IM compared with 3DCRT.

The mean heart doses were 8.95 Gy, 8.00 Gy, 7.22 Gy, and 6.73 Gy for tHD-VMAT, M-VMAT, 3DCRT, and HD-VMAT, respectively. Moreover, there was a significant difference in D_{mean} among HD-VMAT, tHD-VMAT, and M-VMAT. Darby et al. [15] assessed the effect of an increased heart dose in 963 patients with cardiac disease and 1,205 control patients based on the relationship between cardiac disease (e.g., myocardial infarction, coronary artery reconstruction, and death from isch-

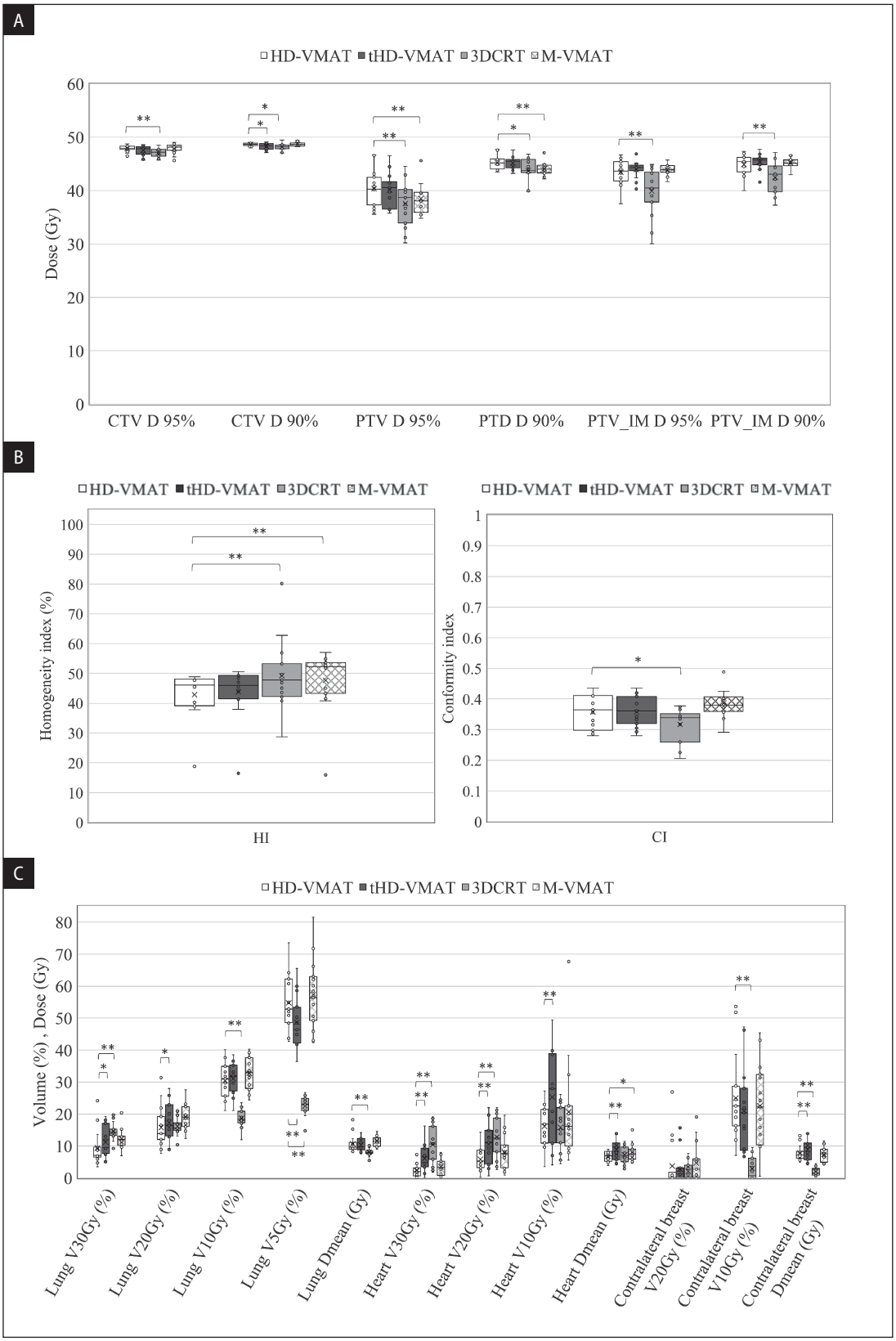

Figure 1. Comparisons of dose indices among HD-MLC, tHD-VMAT, 3DCRT, and M-VMAT. **A.** Target doses; **B.** Homogeneity index (HI) and conformity index (CI); **C.** Organs at risk. **p < 0.01, *p < 0.05. HD-VMAT — three-arc volumetric modulated arc radiotherapy using HD-MLC; tHD-VMAT — tangential volumetric modulated arc radiotherapy using HD-MLC; 3DCRT — three-dimensional conformal radiotherapy; M-VMAT — volumetric modulated arc radiotherapy using Millennium 120-leaf MLC; CTV — clinical target volume; PTV — planning target volume; D — dose; IM — internal mammary

Table 1. Dosing parameters according to radiotherapy plan

Dose parameters	HD-VMAT	tHD-VMAT	3DCRT	M-VMAT
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
CTV				
D95% [Gy]	47.90 ± 0.59	47.56 ± 0.9	47.13 ± 0.81	48.07 ± 0.46
D90% [Gy]	48.65 ± 0.32	48.31 ± 2.54	48.19 ± 0.66	48.69 ± 0.33
PTV				
D95% [Gy]	39.93 ± 3.04	40.13 ± 2.96	37.60 ± 4.14	38.52 ± 2.75
D90% [Gy]	45.07 ± 1.12	45.20 ± 1.20	43.76 ± 2.26	44.11 ± 1.17
PTV_IM				
D95% [Gy]	43.53 ± 2.47	43.98 ± 1.58	39.92 ± 4.58	43.96 ± 0.94
D90% [Gy]	45.07 ± 1.12	45.42 ± 1.43	42.49 ± 3.03	45.28 ± 0.89
Lung				
V30 Gy (%)	9.43 ± 5.46	11.25 ± 4.87	14.59 ± 2.65	12.29 ± 2.93
V20 Gy (%)	15.80 ± 6.48	17.40 ± 6.02	16.20 ± 2.73	19.07 ± 3.83
V10 Gy (%)	30.49 ± 5.38	31.00 ± 4.68	18.74 ± 2.91	32.67 ± 4.99
V5 Gy (%)	54.80 ± 8.41	48.71 ± 7.81	22.49 ± 3.01	57.34 ± 10.78
D_{mean} [Gy]	10.75 ± 2.87	10.38 ± 1.94	8.17 ± 1.28	11.51 ± 1.59
Heart				
V30 Gy (%)	2.33 ± 2.01	6.10 ± 4.41	10.52 ± 5.76	3.54 ± 2.71
V20 Gy (%)	5.86 ± 3.55	10.53 ± 6.09	12.79 ± 6.24	8.05 ± 5.37
V10 Gy (%)	16.17 ± 6.37	25.35 ± 13.91	15.83 ± 6.75	20.69 ± 15.67
D_{mean} [Gy]	6.73 ± 1.54	8.95 ± 3.13	7.22 ± 2.77	8.00 ± 2.73
Breast_Rt				
V20 Gy (%)	3.78 ± 7.73	2.78 ± 4.68	2.09 ± 2.8	4.71 ± 5.90
V10 Gy (%)	25.03 ± 13.46	20.93 ± 13.15	2.98 ± 3.53	22.59 ± 13.02
D_{mean} [Gy]	7.84 ± 2.29	6.38 ± 2.15	1.91 ± 1.32	7.44 ± 2.20
Homogeneity index (%)	42.85 ± 7.76	43.84 ± 8.49	49.23 ± 11.55	47.69 ± 10.26
Conformity index	0.36 ± 0.05	0.36 ± 0.05	0.32 ± 0.06	0.39 ± 0.05

CTV — clinical target volume; PTV — planning target volume; PTV_IM — PTV internal mammary node; VMAT — volumetric modulated arc radiotherapy; HD-VMAT — three-arc VMAT using HD-MLC; tHD-VMAT — two tangential arcs and one arc VMAT using HD-MLC; 3DCRT — three-dimensional conformal radiotherapy; M-VMAT — two-arc VMAT using Millennium 120-leaf MLC; Breast_Rt — contralateral breast

emic cardiac disease) and the heart dose. The incidence of cardiac disease increased by 7.4% per Gy with the increase in the mean heart dose. In terms of the normal heart dose index, Gagliardi et al. [16] predicted that if V25 Gy < 10% (2 Gy per fraction) is a model-based index, the mortality rate due to cardiac disease is ≤ 1% (15 years after radiotherapy). Wei et al. [17] reported that the risk of pericardial effusion increased significantly at a mean pericardial dose of > 26.1 Gy and pericardial V30 > 46%. In this study, HD-VMAT resulted in the lowest heart D_{mean} and V30 Gy. Moreover, the heart V20 and V30 Gy were significantly lower for HD-VMAT than tHD-VMAT and 3DCRT. Therefore, HD-VMAT does not appear to be a greater risk factor for cardiac disease compared with 3DCRT, tHD-VMAT, and M-VMAT.

Marks et al. [18] recommended limiting the V20 Gy and mean lung dose to 30–35% and 20–23 Gy, respectively, to restrict the risk of radiation pneumonitis to ≤ 20%, based on previous review articles. Moreover, Chao et al. [19] found that the ipsilateral lung V40 Gy was the most significant predictive factor for the Lyman–Kutcher–Burman normal tissue complication probability model in radiation-induced pneumonitis. In this study, the lung V20 and D_{mean} for all plans were less than 35% and 20 Gy, respectively. Although the lung D_{mean} and low doses (< V10 Gy) of HD-VMAT were significantly higher than those of

Table 2. Difference in each dosing parameter of three-arc VMAT using HD-MLC (HD-VMAT) relative to other radiotherapy plans

Dose parameters	tHD-VMAT		3DCRT		M-VMAT	
	Difference	p-value	Difference	p-value	Difference	p-value
CTV						
D95% [Gy]	−0.34	0.211	−0.77	0.008 **	0.17	0.865
D90% [Gy]	−0.34	0.001 *	−0.45	0.027 *	0.04	0.733
PTV						
D95% [Gy]	0.20	0.308	−2.33	0.001 **	−1.40	0.001 **
D90% [Gy]	0.13	0.916	−1.31	0.020 *	−0.96	0.001 **
PTV_IM						
D95% [Gy]	0.45	0.570	−3.61	0.009 **	0.43	0.427
D90% [Gy]	0.35	0.394	−2.58	0.006 **	0.21	0.394
Lung						
V30 Gy (%)	1.82	0.023 *	5.16	0.009 **	2.93	0.061
V20 Gy (%)	1.60	0.019 *	0.40	0.427	3.32	0.061
V10 Gy (%)	0.51	0.279	−11.75	0.001 **	2.25	0.191
V5 Gy (%)	−6.10	0.003 **	−32.31	0.001 **	2.54	0.650
D_{mean} [Gy]	−0.37	0.733	−2.58	0.002 **	0.76	0.069
Heart						
V30 Gy (%)	3.78	0.001 **	8.20	0.001 **	1.22	0.061
V20 Gy (%)	4.67	0.004 **	6.93	0.002 **	2.19	0.069
V10 Gy (%)	9.18	0.004 **	−0.34	0.776	4.51	0.570
D_{mean} [Gy]	2.23	0.002 **	0.50	0.532	1.27	0.031 *
Breast_Rt						
V20 Gy (%)	−1.00	0.583	−1.69	0.929	0.93	0.069
V10 Gy (%)	−4.09	0.069	−22.04	0.001 **	−2.43	0.334
D_{mean} [Gy]	−1.46	0.002 **	−5.93	0.001 **	−0.40	0.334
Homogeneity index	0.99	0.069	6.38	0.001 **	4.84	0.001 **
Conformity index	0.00	0.875	−0.04	0.023 *	0.03	0.112

CTV — clinical target volume; PTV — planning target volume; PTV_IM — PTV internal mammary node; VMAT — volumetric modulated arc radiotherapy; tHD VMAT — two tangential arcs and one arc VMAT using HD-MLC; 3DCRT — three-dimensional conformal radiotherapy; M-VMAT, two-arc VMAT using Millennium 120-leaf MLC; Breast_Rt — contralateral breast; Difference, the respective parameter of the indicated plan minus the HD-VMAT parameter. **p < 0.01, *p < 0.05

3DCRT, the high doses (> V30 Gy) of HD-VMAT were lower than those of 3DCRT. High doses (> V20 Gy) of HD-VMAT were lower than those of tHD-VMAT, and the D_{mean} was comparable between the two plans. The lung doses of HD-VMAT were comparable with those of M-VMAT. Therefore, HD-VMAT did not present a higher risk of radiation pneumonitis compared with 3DCRT; however, it presented a lower and similar risk compared with tHD-VMAT and M-VMAT, respectively.

As radiation exposure of the contralateral breast can induce secondary cancers, exposure should be avoided as much as possible. In our study, the mean dose to the contralateral breast ranked in the order of HD-VMAT > M-VMAT > tHD-VMAT > 3DCRT. We believe that the dose to the contralateral breast was increased by the VMAT plans because of the high dose applied to the IMN. This correlates with the increased OS by sufficient irradiation of the IMN; therefore, depending on the age and risk factors of the patient, the advantages of IMN exposure may outweigh the disadvantages of contralateral breast exposure.

Zhao et al. [20] evaluated radiotherapy of the left mammary gland, including the IMN, using 3DCRT and VMAT. They found that VMAT reduced the OAR dose without lowering the target coverage based on fixed-gantry IMRT and VMAT

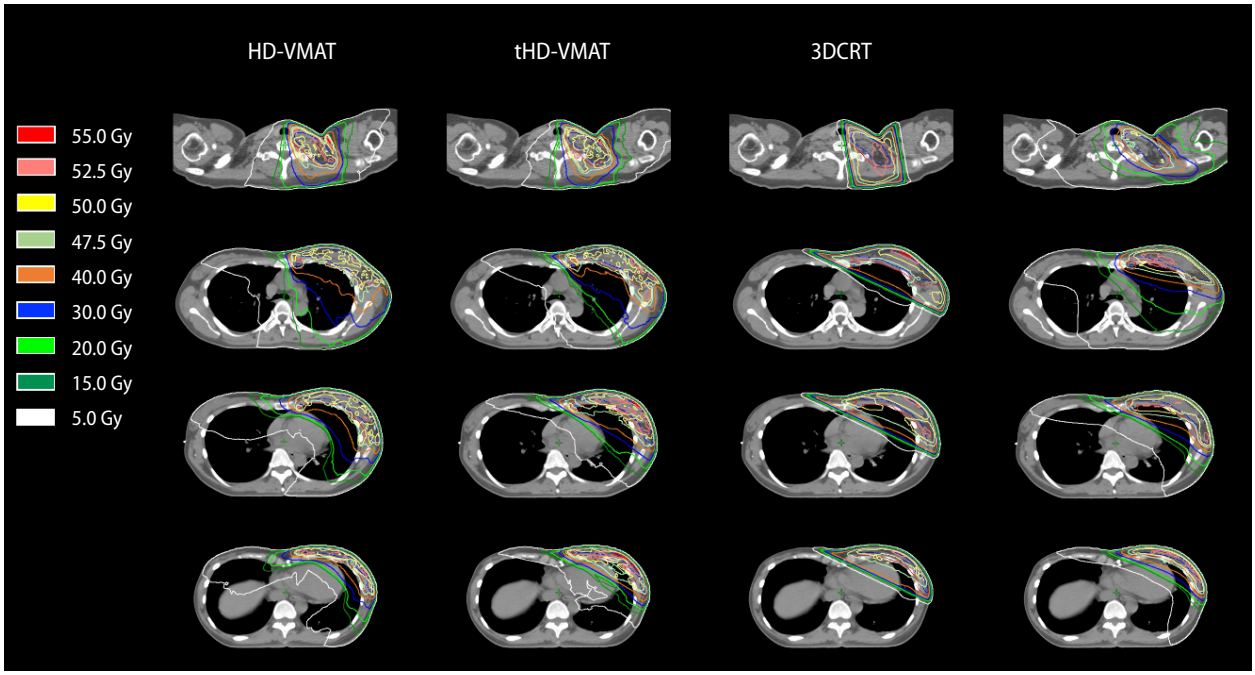

Figure 2. Dose distributions of volumetric modulated arc radiotherapy using high-definition multi-leaf collimator (HD-MLC) (first column), tangential volumetric modulated arc radiotherapy using HD-MLC (second column), and three-dimensional conformal radiotherapy (third column). Dose distributions of volumetric modulated arc radiotherapy using Millennium 120-leaf MLC (fourth column). The dose in the isodose curve follows the left label. The contours shown are the clinical target volume (navy) and planning target volume (red)

treatment plans in 24 patients. The mean heart doses of fixed-gantry IMRT, one-arc VMAT, and two-arc VMAT were 10.6 Gy, 7.8 Gy, and 7.2 Gy, respectively. Thus, the mean heart dose in our study was approximately the same as that reported by Zhao et al. [20] When compared with the studies of Xi et al. [21] and Zhao et al. [22], the mean heart dose was lower than that in our study when left breast irradiation was performed using VMAT; however, it should be noted that the IMN was not included in the target volume, which may have resulted in the reduction of this dose (Supplementary File — Tab. S2).

In comprehensive comparisons with other methods, HD-VMAT delivered a higher dose to the target volume, including PTV_IM, without increasing the risk to the heart and lungs. Moreover, HD-VMAT delivered a better dose distribution, consistent with the target doses, compared with 3DCRT, without increasing the heart D_{mean} or V20 Gy. The heart D_{mean} and lung V20 Gy of HD-VMAT were lower than those of tHD-VMAT; meanwhile, the target doses were equivalent. In tHD-VMAT, we consider that the high dose to the heart and lung can adequately irradiate the PTV_IM due to the restricted irradiation angle. The heart D_{mean} was lower and the HI inferior for HD-VMAT than M-VMAT; however, the target dose indices were equivalent between the plans. Although the dose may vary depending on the number of arcs, collimator angle, and optimization parameters, it was clear that HD-VMAT was not inferior to M-VMAT.

This study had several limitations. Because the field size and irradiation angle were different for each plan, it was impossible to maintain the same parameters for optimization. Therefore, the doses to the targets and OARs can be changed depending on the optimization parameters and skills of the medical physicists. However, in this case, the variation among the plans was eliminated by the set criteria. In addition, the target doses for each VMAT plan were approximately the same. It was assumed that more arcs can be used in M-VMAT to improve the distribution, but in this study, we used two arcs, the most commonly used number [20, 22, 23]. Deep-inspiration breath-hold effectively reduces the dose to the heart [24], but this study only examined the dose distribution using free-breath CT images.

Conclusions

The dose distribution of HD-VMAT can obtain excellent coverage of the target compared with 3DCRT, without increasing the heart D_{mean} or V20 Gy. HD-VMAT was superior to tHD-VMAT and was not inferior to M-VMAT. Therefore, VMAT using HD-MLC is useful for patients undergoing postoperative irradiation of breast and regional lymph nodes, including IMN.

Conflicts of interest

None declared.

Funding

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Ethical permission

The study was approved by the institutional review board for clinical research at Tokai University (18R126).

Author contributions

Data collection, data analysis, writing the original draft: Y.M.. Review and editing as a medical physicist: N.F. Review and editing as a doctor: E.K., T.A., R.N., T.F., T.Ka., T.Ku., T.M., E.M., and A.S.. Review and editing as a radiologic technologist: Y.O. and K.S.

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