



Impact of Internal Mammary Node Irradiation and Thoracic Lateral Diameter on Organ-at-Risk Doses and Normal Tissue Complication Probability in Free-Breathing Right Breast Volumetric Modulated Arc Therapy

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OBJECTIVE

To evaluate the independent impact of internal mammary node irradiation (IMNI) and thoracic morphology on organ-at-risk (OAR) doses and normal tissue complication probability (NTCP) in free-breathing right breast volumetric modulated arc therapy (VMAT), and to identify computed tomography (CT)-based markers of higher OAR dose.

METHODS

Fifty consecutive right-sided breast cancer patients treated with free-breathing VMAT were retrospectively analyzed. Doses were converted to the equivalent dose in 2-Gy fractions (EQD2; $\alpha/\beta=3$ Gy). Pulmonary NTCP (Lyman-Kutcher-Burman model) and major adverse cardiac event risk (Darby model) were calculated. Multivariate analysis identified independent OAR-dose predictors.

RESULTS

IMNI (13 patients, 26%) significantly increased lung Dmean, pulmonary NTCP, and cardiac Dmean on univariate analysis (all $p<0.001$). After adjustment, IMNI independently predicted lung Dmean ($\beta=+0.97$ Gy; $p=0.029$), lung V5 ($\beta=+8.28\%$; $p=0.024$), cardiac Dmean ($\beta=+0.43$ Gy; $p=0.027$), and NTCP ($\beta=+0.60\%$; $p=0.020$). Thoracic lateral diameter independently correlated with lung Dmean ($\rho=0.368$; $p=0.009$) and cardiac Dmean ($\rho=0.311$; $p=0.028$). The Haller Index showed no significant correlation with OAR doses.

CONCLUSION

IMNI independently increases lung and cardiac doses and thoracic lateral diameter independently predicts OAR dose in free-breathing right-breast VMAT. These markers may identify higher-risk patients who could be prioritized for deep inspiration breath-hold (DIBH) evaluation, pending confirmation in paired planning studies.

Keywords: Breast cancer radiotherapy; internal mammary node irradiation; normal tissue complication probability; organ-at-risk dose; volumetric modulated arc therapy.

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INTRODUCTION

Breast cancer is the most common malignancy among women worldwide, with approximately 2.3 million incident cases annually.[1] Adjuvant radiotherapy (RT) substantially reduces locoregional recurrence and improves breast cancer-specific survival following breast-conserving surgery and mastectomy.[2] However, irradiation of the thoracic region inevitably exposes the ipsilateral lung and heart to incidental radiation, with the potential for long-term cardiopulmonary complications.

The landmark study by Darby et al.[3] demonstrated that the risk of major adverse cardiac events (MACE) increases linearly with the mean heart dose by 7.4% per gray, commencing within five years of irradiation and persisting for decades. Radiation-induced pneumonitis, a clinically relevant dose-limiting toxicity, has been quantitatively characterized through dose-volume metrics, with lung mean dose and V20 serving as principal predictors within the Lyman-Kutcher-Burman (LKB) modelling framework.[4]

Internal mammary node irradiation (IMNI) has been increasingly incorporated into locoregional RT protocols for node-positive and high-risk breast cancer following randomized evidence of survival benefits from comprehensive regional nodal irradiation.[5] However, incorporating internal mammary targets substantially expands the irradiated volume, raising concerns about elevated OAR dose exposure.[6] In right-sided breast cancer, the cardiac anatomy results in comparatively lower baseline mean heart doses than in left-sided irradiation; nevertheless, the incremental OAR dose burden attributable to IMNI remains clinically relevant, particularly given the proximity of the right coronary artery, lung base, and liver to the internal mammary chain.

Deep-inspiration breath-hold (DIBH) is an established respiratory gating technique that reduces cardiac and pulmonary doses by increasing thoracic volume and creating greater geometric separation between the irradiated target and critical structures.[7] Recent dosimetric studies have demonstrated meaningful OAR sparing with DIBH in right-sided breast cancer, particularly when IMNI is included.[8] Despite these findings, DIBH requires additional institutional resources, extended simulation times, and patient cooperation. Identifying pretreatment CT-based morphological features associated with higher free-breathing OAR dose could, in principle, help flag patients for whom more advanced dose-sparing approaches merit prospective evaluation.

This study aimed to assess the independent impact of IMNI and thoracic morphological parameters, including lateral diameter, AP diameter, longitudinal diameter, the Vertical-Transverse Lung Ratio, and the Haller Index, on OAR dose-volume indices and NTCP in a homogeneous free-breathing right breast VMAT cohort and to identify determinants of free-breathing OAR dose that may serve as candidate criteria for prospective DIBH evaluation.

MATERIALS AND METHODS

Patients and Ethics

This retrospective single-institution study enrolled 50 consecutive patients with right-sided breast cancer who were treated with adjuvant RT at the Batman Training and Research Hospital Department of Radiation Oncology between August 2025 and May 2026. Ethical approval was obtained from the Non-Interventional Research Ethics Committee of the Batman Training and Research Hospital (No: 481, Date: 14/05/2026). This study was conducted in accordance with the Declaration of Helsinki. All patients received free-breathing VMAT, and those planned with DIBH were excluded to ensure cohort homogeneity. Written consent was obtained from the patients.

Treatment Planning

Treatment plans were generated using the Monaco 6.2 planning system (Elekta AB, Stockholm, Sweden) and delivered using an Elekta Versa HD linear accelerator. Contouring was performed by a single radiation oncologist according to the ESTRO consensus guidelines.[9] Hypofractionated schedule: 40.05 Gy in 15 fractions (simultaneous integrated boost 48 Gy/15 fr for breast-conserving surgery patients). Conventional schedule: 50 Gy in 25 fractions with a sequential boost of 10 Gy/5 fractions. IMNI was selectively applied based on the axillary nodal status and medial tumor location.

Dosimetric Parameters and EQD2 Conversion

DVH parameters were extracted for the ipsilateral lung (Dmean, V5, and V20) and heart (Dmean and V5). All doses were converted to EQD2 using a linear-quadratic model ($\alpha/\beta=3$ Gy). For the hypofractionated plans, the V20 threshold was adjusted to V16 and V5 to V4 in the physical dose, corresponding to 20 Gy and 5 Gy EQD2, respectively.

Thoracic Morphological Measurements

Thoracic dimensions were measured on planning CT, including the AP, lateral, and longitudinal diameters. The Haller Index (HI = lateral² / (AP × sagittal)) was

Table 1 Patient and thoracic morphological characteristics by internal mammary node irradiation status

Parameter	Total (n=50)	No IMNI (n=37)	IMNI (n=13)	p
Surgery, n (%)				
Breast-conserving surgery	28 (56)	21 (56.8)	7 (53.8)	0.851
Mastectomy	22 (44)	16 (43.2)	6 (46.2)	–
Fractionation, n (%)				
Hypofractionated (40.05 Gy/15 fr)	22 (44)	19 (51.4)	3 (23.1)	0.149
Conventional (50 Gy/25 fr)	28 (56)	18 (48.6)	10 (76.9)	–
Nodal Irradiation, n (%)				
Peripheral lymphatic RT	35 (70)	22 (59.5)	13 (100)	0.003**
Internal mammary RT	13 (26)	–	13 (100)	–
Thoracic measurements				
AP diameter (cm)	10.26±1.41	10.31±1.39	10.10±1.50	0.664
Lateral diameter (cm)	21.96±1.19	21.84±1.20	22.38±1.12	0.185
Longitudinal diameter (cm)	14.30±1.62	14.27±1.68	14.38±1.45	0.834
Haller index	2.18±0.35	2.19±0.36	2.16±0.34	0.820
Right lung volume (cc)	1341±186	1335±191	1357±176	0.704
Cardiac volume (cc)	625±104	618±110	644±87	0.419
Breast/mastectomy volume (cc)	722±484	700±464	786±545	0.602

** $p < 0.01$. Continuous data are presented as mean $\pm$ SD, and categorical data are presented as n (%). Group comparisons: independent samples t-test or Fisher's exact test as appropriate. AP: Anterior-posterior; BCS: Breast-conserving surgery; GTV: Gross tumor volume; HI: Haller Index; IMNI: Internal mammary node irradiation; RT: Radiotherapy.

calculated. The right lung, cardiac, and breast/GTV volumes were derived from CT-based contours. All measurements were performed by a single observer using a digital caliper.

NTCP Modelling

Pulmonary NTCP was calculated using the LKB model (TD50=30.5 Gy, $m=0.37$, $n=0.99$).^[10] Cardiac MACE risk was estimated using the Darby linear model: MACE risk = $3\% \times (1 + 0.074 \times \text{cardiac Dmean})$.^[3]

Statistical Analysis

Normality was assessed using the Shapiro-Wilk test. Normally distributed continuous variables are expressed as mean $\pm$ standard deviation (SD) and compared using the independent-samples t-test. Non-normally distributed variables are expressed as medians (25th–75th percentile) and were compared using the Mann-Whitney U test. Categorical variables were compared using Fisher's exact test. Spearman's rank correlation was used to assess the bivariate associations between the morphological parameters and the OAR dose metrics, given the non-normal distribution of several dose parameters. Multivariate linear regression, adjusted for fractionation schedule, surgical type, right lung volume, and peripheral nodal irradiation, identified independent predictors of OAR dose. Multicollinearity was assessed using variance inflation factors (VIFs), with values <5 considered acceptable. The robustness of the IMNI associations

was further evaluated by restricting the analysis to patients who received regional nodal irradiation, by modelling nodal treatment as a three-level ordinal variable (breast/chest-wall only, regional nodal irradiation without IMNI, and regional nodal irradiation with IMNI), and by re-estimating the primary model using a non-parametric bootstrap (percentile confidence intervals over 2000 resamples), which makes no distributional assumption while targeting the same conditional-mean estimand. Linear regression was used descriptively to quantify explained variance and independent associations rather than for formal parametric inference. Cohen's d quantified effect sizes. Analyses were performed using Python 3.11 (pandas 2.1, scipy 1.11, statsmodels 0.14) and SPSS 26.0 (IBM Corp., Armonk, NY, USA). Statistical significance was set at $p < 0.05$ (two-tailed).

RESULTS

Patient and Treatment Characteristics

The cohort comprised 50 patients with right-sided breast cancer who were treated with free-breathing VMAT. Breast-conserving surgery was performed in 28 (56.0%) patients and mastectomy in 22 (44.0%) patients. Hypofractionated RT was used in 22 (44.0%) and conventional fractionation in 28 (56.0%). Peripheral lymphatic RT was administered to 35 (70.0%) patients and IMNI to 13 (26.0%). Patient characteristics and between-group comparisons are shown in Table 1.

Table 2 OAR dose parameters and NTCP estimates by internal mammary node irradiation status (EQD2, $\alpha/\beta=3$ Gy)

Parameter (EQD2, $\alpha/\beta=3$ Gy)	Total (n=50)	No IMNI (n=37)	IMNI (n=13)	p
Ipsilateral lung				
Dmean (Gy) [†]	9.95 (8.43–11.00)	8.95 (6.80–10.50)	11.00 (10.20–11.00)	<0.001***
V20 (%) [†]	15.5 (12.0–19.0)	13.0 (11.0–17.0)	18.0 (17.0–20.0)	0.003**
V5 (%)	45.30±11.64	42.11±9.99	54.38±10.71	<0.001***
NTCP Pneumonitis (%) [†]	2.97 (1.64–4.20)	2.81 (1.79–3.82)	4.20 (3.60–4.20)	<0.001***
Heart				
Dmean (Gy)	2.15±0.64	1.97±0.56	2.64±0.56	<0.001***
V5 (%) [†]	1.35 (0.10–7.60)	1.09 (0.10–6.00)	8.70 (5.48–10.00)	0.002**
MACE Risk (%) [‡]	3.48±0.14	3.44±0.13	3.59±0.13	<0.001***

[†]: Non-normally distributed (Shapiro-Wilk $p<0.05$): median (25th–75th percentile); Mann-Whitney U test. Normally distributed: mean±SD; independent-samples t-test. [‡]: MACE risk: Darby model (baseline 3%×[1+0.074×Dmean]). **: $p<0.01$; ***: $p<0.001$. Spearman's rank correlation coefficients are denoted as r . EQD2: Equivalent dose in 2-Gy fractions; IMNI: Internal mammary node irradiation; MACE: Major adverse cardiac event; NTCP: Normal tissue complication probability.

No significant differences were observed between the IMNI and non-IMNI groups in terms of surgical type, fractionation, thoracic measurements, or anatomical volumes (all $p>0.05$); the only significant difference was a higher peripheral RT rate in the IMNI group (100% vs. 59.5%; $p=0.003$). Fifteen patients received breast or chest-wall irradiation alone, 22 received comprehensive regional nodal irradiation without IMNI, and all 13 IMNI patients also received regional nodal irradiation; the 22 patients who received regional nodal irradiation without IMNI served as the reference stratum enabling the effect of IMNI to be separated from that of comprehensive regional nodal irradiation.

OAR Dose Distribution and NTCP

Overall, the median ipsilateral lung Dmean was 9.95 (IQR: 8.43–11.00) Gy, median lung V20 was 15.5 (IQR: 12.0–19.0) %, lung V5 was 45.30±11.64%, cardiac Dmean was 2.15±0.64 Gy, and median cardiac V5 was 1.35 (IQR: 0.10–7.60) %. The median pulmonary NTCP was 2.97 (IQR: 1.64–4.20) % (range 1.39–5.54%), and the mean MACE risk was 3.48±0.14%.

Impact of Internal Mammary Node Irradiation

Univariate analysis demonstrated that IMNI was significantly associated with higher values for all OAR dose endpoints, with large effect sizes (Cohen's $d=1.27$, 1.18, and 1.18 for lung Dmean, lung V5, and cardiac Dmean, respectively) (Table 2). The rate of lung V20 exceeding 15% was 92% in patients with IMNI versus 46% in patients without IMNI ($p=0.004$). Cardiac Dmean exceeded 2.5 Gy in 54% of IMNI patients versus 14% of non-IMNI patients ($p=0.007$).

After multivariate adjustment, IMNI remained an independent predictor of lung Dmean ($\beta=+0.97$ Gy, 95% CI: +0.10 to +1.85; $p=0.029$; $R^2=0.616$), lung

Table 3 Multivariate linear regression: Independent effect of IMNI on OAR doses after adjustment for fractionation, surgical type, right lung volume, and peripheral nodal irradiation

Outcome	IMNI β (Gy or %)	95% CI	p
Lung Dmean (Gy)	+0.97	+0.10 to +1.85	0.029*
Lung V20 (%)	+1.81	-0.45 to +4.07	0.114
Lung V5 (%)	+8.28	+1.14 to +15.41	0.024*
Heart Dmean (Gy)	+0.43	+0.05 to +0.81	0.027*
Heart V5 (%)	+2.95	-1.30 to +7.20	0.168
NTCP Pneumonitis (%)	+0.60	+0.10 to +1.11	0.020*

*: $p<0.05$. Covariates: IMNI, fractionation (hypofractionated vs. conventional), surgery (BCS vs. mastectomy), right lung volume, and peripheral lymphatic RT. CI: Confidence interval; IMNI: Internal mammary node irradiation; NTCP: Normal tissue complication probability.

V5 ($\beta=+8.28\%$, 95% CI: +1.14 to +15.41; $p=0.024$; $R^2=0.338$), cardiac Dmean ($\beta=+0.43$ Gy, 95% CI: +0.05 to +0.81; $p=0.027$; $R^2=0.372$), and pulmonary NTCP ($\beta=+0.60\%$, 95% CI: +0.10 to +1.11; $p=0.020$; $R^2=0.625$). Lung V20 and cardiac V5 did not retain significance after adjustment (Table 3). No evidence of problematic multicollinearity was observed among the regression covariates (all VIF values <2; IMNI VIF=1.21, peripheral RT VIF=1.72).

Because all IMNI patients also received comprehensive regional nodal irradiation, additional analyses were performed to separate the two effects. When the analysis was restricted to the 35 patients receiving regional nodal irradiation, IMNI remained independently associated with cardiac Dmean ($\beta=+0.48$ Gy; $p=0.047$), while lung Dmean ($\beta=+0.99$ Gy; $p=0.054$) and lung V5 ($\beta=+8.07\%$; $p=0.052$) showed similar effect sizes with borderline statistical significance. Mod-

Table 4 Robustness of the independent effect of IMNI on organ-at-risk doses: Primary OLS model and non-parametric bootstrap

Outcome	Model	IMNI β (Gy or %)	95% CI	p
Lung Dmean (Gy)	OLS (primary)	+1.03	+0.09 to +1.97	0.032*
	Bootstrap (2000 resamples)	+1.01	+0.23 to +1.82	0.013*
Lung V5 (%)	OLS (primary)	+8.28	+1.14 to +15.41	0.024*
	Bootstrap (2000 resamples)	+8.00	+0.45 to +16.67	0.035*
Heart Dmean (Gy)	OLS (primary)	+0.47	+0.06 to +0.89	0.026*
	Bootstrap (2000 resamples)	+0.45	-0.03 to +0.95	0.068

*: $p < 0.05$. β denotes the adjusted IMNI coefficient (increment attributable to internal mammary node irradiation) from the primary covariate set (IMNI, fractionation, surgery, right lung volume, and peripheral lymphatic RT; $n=50$). Because several dose parameters were non-normally distributed and the sample was modest, the ordinary least-squares (OLS) estimates were re-evaluated using a non-parametric bootstrap (percentile confidence intervals over 2000 resamples), which makes no distributional assumption while targeting the same conditional-mean estimand. Doses are expressed in EQD2 ($\alpha/\beta=3$ Gy). The IMNI associations for the lung endpoints were preserved under bootstrap resampling; the cardiac Dmean association was directionally consistent but attenuated to borderline significance, consistent with the modest sample size and the exploratory nature of the analysis. CI: confidence interval; IMNI: internal mammary node irradiation.

elling nodal treatment as a three-level ordinal variable demonstrated a stepwise dose gradient, with IMNI adding an incremental dose burden beyond regional irradiation alone (lung Dmean: +2.96 Gy vs. +1.93 Gy; cardiac Dmean: +0.96 Gy vs. +0.48 Gy, relative to breast/chest-wall irradiation). Re-estimation of the primary model using a non-parametric bootstrap (2000 resamples; Table 4) confirmed the robustness of the IMNI associations for the lung endpoints (lung Dmean $p=0.013$; lung V5 $p=0.035$), whereas the association with cardiac Dmean remained directionally consistent ($\beta=+0.45$ Gy) but did not reach conventional statistical significance ($p=0.068$), consistent with the modest sample size and exploratory nature of the analysis.

Thoracic Geometry as a Predictor of OAR Dose
Among the morphological parameters, the lateral thoracic diameter correlated significantly with lung Dmean ($\rho=0.368$, $p=0.009$), pulmonary NTCP ($\rho=0.368$, $p=0.009$), cardiac Dmean ($\rho=0.311$, $p=0.028$), and MACE risk ($\rho=0.311$, $p=0.028$). These associations were retained in the multivariate models after adjusting for IMNI and fractionation. The Haller Index showed no significant correlation with any OAR dose parameter (all $p > 0.05$; $|\rho|$ range: 0.016–0.076). The longitudinal diameter showed no significant correlation with lung V5 ($\rho=-0.226$, $p=0.114$).

DISCUSSION

This study demonstrates that IMNI independently increases the ipsilateral lung dose, pulmonary NTCP, and cardiac mean dose in free-breathing right breast VMAT, even after adjusting for the fractionation schedule and other treatment-related confounders. Ad-

ditionally, the thoracic lateral diameter independently predicted the lung and cardiac OAR dose, providing a readily measurable pretreatment CT parameter associated with higher OAR dose under free-breathing treatment. Because the regression analyses were exploring and performed in a relatively small cohort, the observed associations should be interpreted as hypothesis-generating.

Our finding of elevated OAR doses with IMNI is consistent with the published dosimetric evidence. Refsgaard et al.[11] reported a mean ipsilateral lung dose increase of 2.7 Gy and an approximately 20% increase in irradiated volume with IMNI versus non-IMNI locoregional RT plans. Regional nodal irradiation, including IMNI, has consistently been shown to increase cardiac and lung dose-volume parameters compared with breast or chest wall irradiation alone. [12] Our data confirm these findings in a right-sided free-breathing VMAT-specific cohort with EQD2 normalization, a methodological refinement enabling valid cross-comparison across mixed fractionation schedules, which is a common limitation of prior dosimetric studies.

The independent predictive value of IMNI for cardiac Dmean ($\beta=+0.43$ Gy after multivariate adjustment) has a direct clinical significance. Applying the Darby model,[3] this increment corresponds to an approximate 3.2% relative increase in MACE risk attributable specifically to IMNI. While the absolute cardiac risks associated with right-sided breast RT are lower than those associated with left-sided irradiation, the cumulative lifetime risk — particularly in younger patients, those with pre-existing cardiovascular comorbidities, or those receiving anthracycline-based chemotherapy — may reach clinical relevance.[13] Given

that the right coronary artery passes through the anterior aspect of the heart near the medial fields, minor increases in mean heart dose driven by IMNI cannot be dismissed as clinically negligible.

The IMNI-related lung dose elevation has important implications for pneumonitis-risk stratification. Consistent with QUANTEC recommendations,[14] an institutional lung V20 threshold of 15% was used as a practical risk boundary in the breast RT context, which is a lower threshold than the 30–35% recommended for lung cancer RT, reflecting the expectation of lower lung doses in adjuvant breast irradiation. The fact that 92% of IMNI patients exceeded this threshold versus only 46% of non-IMNI patients ($p=0.004$) identifies IMNI candidates as the highest-risk free-breathing subgroup, in whom prospective evaluation of DIBH benefit is warranted.

DIBH has been shown to meaningfully reduce OAR doses in right-sided breast cancer RT, particularly when IMNI is included. Yoo et al.[15] demonstrated reductions in ipsilateral lung Dmean from 15.9 to 12.6 Gy and cardiac Dmean from 2.5 to 1.6 Gy with DIBH in right-sided patients receiving regional nodal irradiation. A treatment planning study by Brown et al.[8] similarly confirmed considerable OAR sparing with DIBH in right-sided locoregional RT plans, including IMNI. Our data identified patients with IMNI as the highest-risk free-breathing subgroup, in whom the potential benefit of more advanced dose-sparing techniques would be worth evaluating prospectively.

To our knowledge, the identification of the lateral thoracic diameter as an independent predictor of lung and cardiac OAR dose is novel in the right-sided breast RT setting. The mechanistic basis is straightforward: A wider thorax necessitates wider tangential beam apertures that intercept a proportionally larger volume of the ipsilateral lung. Critically, the lateral diameter remained significant after adjustment for lung volume, indicating that thoracic width conveys distinct geometric information beyond volumetric parameters. The lateral diameter is directly measurable from any planning CT without specialized software, making it a readily available candidate parameter for pretreatment risk assessment, pending external validation. External validation is required before adopting specific lateral-diameter thresholds for routine clinical decision-making.

The Haller Index, a thoracic deformity index derived from the AP, sagittal, and lateral diameters, showed no significant correlation with OAR doses in our right-

sided cohort (all $p>0.05$). This differs from the findings of left-sided breast cancer studies, in which thoracic shape may influence cardiac proximity to the irradiated chest wall. In right-sided RT, cardiac exposure is predominantly determined by the medial field extent (IMNI inclusion) rather than thoracic deformity, explaining the lack of HI predictive value. These findings argue against the use of thoracic shape indices as OAR dose predictors in right-sided breast RT.

The LKB-derived pulmonary NTCP estimates (median, 2.97%) and Darby-model MACE estimates (mean, 3.48%) reflect the low OAR doses characteristic of adjuvant breast RT.[16] Their principal utility in this study lies in their use as continuous quantitative outcome variables for multivariate analysis and as individualized risk communication tools, enabling explicit, patient-centered quantification of the incremental OAR risk attributable to IMNI, which may support the informed consent process and facilitate risk-adapted planning decisions.

Limitations of the Study

This study had several limitations. As this was a retrospective single-center analysis, selection bias cannot be excluded. The sample size of 50 patients limited the statistical power of the subgroup analyses. Accordingly, multivariable modelling should be considered exploratory and requires confirmation in larger external datasets. Demographic variables, including patient age and cardiovascular comorbidity profiles, were not available in the dosimetric dataset and could not be included as covariates. The absence of clinical toxicity data precludes the direct validation of NTCP estimates against observed outcomes, and a prospective cohort study with long-term toxicity endpoints is warranted. Because all patients who received IMNI also underwent peripheral lymphatic irradiation, these two variables were strongly associated, which may introduce collinearity into the multivariate models; the IMNI estimates should therefore be interpreted as reflecting comprehensive regional nodal irradiation that included the internal mammary chain. In addition, p-values were not adjusted for multiple comparisons, so borderline associations warrant cautious interpretation. DIBH planning was not performed in this cohort; a paired dosimetric comparison of free-breathing and DIBH plans for individual patients is required to directly quantify patient-specific DIBH benefits. Consequently, the proposed DIBH selection criteria remain inferential and should be validated in paired free-breathing and DIBH planning studies.

CONCLUSION

In free-breathing right breast VMAT, IMNI independently increased the ipsilateral lung dose, pulmonary NTCP, and cardiac mean dose after multivariate adjustment. The thoracic lateral diameter independently predicted lung and cardiac OAR exposure beyond lung volume, whereas the Haller Index did not predict OAR doses in the right-sided context. Patients requiring IMNI, particularly those with a wide lateral thoracic diameter, represent the highest-risk subgroup under free-breathing treatment and may be candidates for prospective DIBH evaluation. These pretreatment CT-based criteria may assist patient stratification for DIBH evaluation; however, external validation and paired DIBH-free-breathing planning studies are required before routine clinical implementation.

Ethics Committee Approval: The study was approved by the Batman Training and Research Hospital Non-Interventional Research Ethics Committee (no: 481, date: 14/05/2026).

Informed Consent: Written consent was obtained from the patients.

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