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Dosimetric comparison of IMRT and VMAT with deep inspiration breath hold or free breathing for right-sided whole breast irradiation

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Abstract

Purpose To compare dosimetric outcomes of intensity-modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT), with and without deep inspiration breath hold (DIBH), in patients with right-sided early-stage breast cancer receiving whole-breast irradiation (WBI) without nodal targets.

Methods Thirty-two patients with node-negative right breast cancer underwent computed tomography simulation in free-breathing (FB) and DIBH. Four plans per patient were generated: IMRT-FB, IMRT-DIBH, VMAT-FB, and VMAT-DIBH. All plans delivered 40 Gy in 15 fractions to the whole breast. Dosimetric comparisons of target and organ-at-risk (OAR) structures were performed using paired analyses and linear mixed-effects models. A Bonferroni-adjusted significance threshold of $p < 0.001$ was applied.

Results VMAT significantly improved target coverage and dose homogeneity compared to IMRT (median PTV V95%: 99.5% vs. 93.4% under FB and 99.5% vs. 92.2% under DIBH, both $p < 0.001$), but resulted in greater low-dose exposure to the left breast (mean dose, V4, and D0.03 cc) and left lung (V5). VMAT also increased right lung doses (V5 and V16, and mean dose) and liver V5 under FB. DIBH significantly reduced various heart, lung, and liver dose parameters without compromising target coverage. Mean heart dose was lowest with IMRT (0.4 Gy). Liver D2cc (median 2.7 Gy IMRT-DIBH, 3.0 Gy VMAT-DIBH, both $p < 0.001$ vs. FB) and V5 (median 0% IMRT-DIBH, 0.1% VMAT-DIBH, both $p < 0.001$ vs. FB) were significantly reduced with DIBH. DIBH had limited effect on reducing right lung V5 but improved higher-dose sparing (V16, V20, and mean dose). Mixed-effects modelling confirmed that VMAT and DIBH independently affected dose metrics. The average beam-on time was longest for VMAT-DIBH (4.6 min) and shortest for IMRT-FB (3.4 min).

Conclusion DIBH improves OAR sparing for right-sided WBI without compromising target coverage, although absolute OAR doses remained low across all techniques. VMAT improves PTV coverage but increases low-dose exposure to normal tissues; however, these findings are specific to the institutional planning approach and delivery

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technology implemented. The combination of VMAT with DIBH should be individualised based on anatomy and clinical resources. These findings support the optional use of DIBH in right-sided WBI where dosimetric optimisation is prioritised.

Keywords breast neoplasms, radiotherapy, intensity-modulated, respiratory-gated radiotherapy, radiation effects, treatment outcome

Introduction

Breast-conserving surgery followed by whole-breast irradiation (WBI) is a standard treatment for early-stage breast cancer, contributing significantly to improved local control and survival outcomes [1, 2]. Minimising radiation exposure to organs-at-risk (OARs) is increasingly important. In left-sided breast cancer, deep inspiration breath-hold (DIBH) is typically employed to displace the heart from the chest wall and reduce cardiac dose [3, 4]. In contrast, right-sided breast radiotherapy has traditionally been delivered under free-breathing (FB), as the heart is generally not directly within the treatment field. However, the right lung and liver can receive unintended dose, particularly in patients with inferiorly located targets [5].

DIBH can offer dosimetric benefits by expanding lung volume and lowering the diaphragm, resulting in reduced lung density and inferior displacement of the liver [6, 7]. Studies have shown that DIBH significantly reduces radiation doses to the heart, liver, and lungs compared to FB in right-sided breast cancer [7–10]. These findings support the potential role of DIBH in improving the therapeutic ratio for right breast radiotherapy.

Concurrently, advancements in treatment planning have led to the use of intensity-modulated techniques such as IMRT and VMAT to enhance dose conformity. While IMRT techniques are effective at sparing contralateral structures, particularly for left-sided treatment, they may be limited in achieving dose homogeneity in patients with complex anatomy [11, 12]. VMAT offers highly conformal dose delivery through continuous arc modulation and has been shown to improve PTV coverage in left-sided breast radiotherapy [13]. In the context of right-sided breast cancer with regional nodal irradiation, VMAT has similarly demonstrated better target coverage and reduced high-dose exposure to the ipsilateral lung and liver compared to tangential IMRT [14]. Holt et al. reported that although VMAT improved ipsilateral lung and liver sparing, it increased mean heart and contralateral breast dose, which could be improved by the application of DIBH [14].

Despite these insights, there remains a critical gap in the literature concerning patients undergoing WBI without regional nodal irradiation. Existing comparative studies on DIBH for right-sided breast cancer have primarily focused on scenarios involving nodal targets [8–10, 14–16], or have examined DIBH in conjunction with conventional tangential or IMRT-based approaches [15, 17, 18]. Whether these benefits extend to this simpler but common indication remains unclear and warrants evaluation. This study aims to address this knowledge gap by directly comparing IMRT and VMAT under both FB and DIBH conditions in the context of right-sided WBI.

Methods

Patient selection and imaging

Patients with right early-stage node-negative breast cancer were selected. All patients had undergone breast-conserving surgery and were candidates for adjuvant radiotherapy to the whole breast only. Each patient had received two planning computed tomography (CT), one under free-breathing (FB) and another under deep inspiration breath hold (DIBH), as part of an institutional protocol to evaluate DIBH. Patients were immobilised in the supine position on a breast board with both arms raised. Respiratory motion was monitored using the Varian Real-Time Position Management™ system (Varian Medical Systems, Palo Alto, CA). For DIBH, patients inhale to approximately 80% of full capacity and maintain breath-hold with visual feedback. FB scans were obtained during normal respiration.

Target and organ-at-risk delineation

The clinical target volume (CTV) was defined as the whole right breast tissue, extending to the pectoralis major, and respecting 5 mm from skin surface, according to Radiation Therapy Oncology Group (RTOG) breast contouring guidelines. A uniform 7 mm margin was added to the CTV to create the planning target volume (PTV), accounting for setup uncertainty; this PTV was cropped to remain 5 mm from the skin. All relevant OARs were contoured on each CT dataset per RTOG contouring atlases: left breast, heart, left anterior descending coronary artery (LAD), bilateral lungs, liver, spinal cord were outlined. Contours were delineated in the treatment planning system Eclipse v16.1 (Varian Medical Systems, Palo Alto, CA, USA).

Treatment planning techniques

Four plans were generated per patient: IMRT-FB, IMRT-DIBH, VMAT-FB, and VMAT-DIBH. All plans were created for a Varian TrueBeam linear accelerator with 6 megavolt photon beams and prescribed 40 Gy in 15 fractions. IMRT employed an inverse-planned multi-beam

technique approximating tangential arrangements, typically using 2–4 beam angles (medial and lateral with optional additional beamlets) to improve homogeneity, optimised with intensity modulation via step-and-shoot segments. VMAT planning used four partial arcs adapted from the institutional template for breast-and-nodal irradiation, with arc angles selected to minimise direct beam entry through the left breast and lung. The planning system optimised beam apertures and multi-leaf collimator positions to achieve target coverage and OAR sparing.

All plans were normalised to achieve the best overall dosimetric balance, rather than fixed to a uniform D95% criterion. Normalisation was adjusted iteratively to optimise target coverage while minimising hot and cold spots and maintaining acceptable OAR doses. Hotspots were limited such that no more than 0.03 cc received > 105% (42 Gy), using auxiliary contours and constraints. Optimisation was then performed to refine OAR sparing while maintaining the chosen PTV normalisation.

Dosimetric evaluation

For each plan, dose-volume histograms (DVHs) were generated to extract relevant dosimetric endpoints. Target coverage was quantified by PTV V95% and PTV V105% as indicators of prescription dose coverage and hotspot volume, respectively. The maximum dose (Dmax), defined as the dose to the hottest 0.03 cc of the PTV, was also recorded to verify that it remained within 107% of the prescribed dose.

To further assess plan quality, the homogeneity and conformity of dose distribution within the target were evaluated. The homogeneity index was calculated using the International Commission on Radiation Units and Measurements 83 formula: [19] homogeneity index = (D2%–D98%)/D50%, where D2% and D98% represent the near-maximum and near-minimum doses to the PTV, and D50% represents the median dose. The conformity index was defined as the ratio of the 95% prescription isodose volume (V95%) to the PTV volume (VPTV), consistent with the RTOG definition [20].

OARs were evaluated using the following metrics: mean heart dose (Gy); heart V20 (percent volume receiving ≥ 20 Gy); right lung V20, V16, and V5 (volume receiving ≥ 20 Gy, ≥ 16 Gy, and ≥5 Gy, respectively) to assess both high-dose exposure and low-dose bath; left lung V5; mean right lung dose; liver D2cc (minimum dose to the hottest 2 cc of liver); liver V5 (volume of liver receiving ≥5 Gy); and left breast dose, recorded as V4 and D0.03 cc to reflect near-maximum exposure. All dose metrics were calculated separately on FB and DIBH plans based on their respective planning CT images.

Statistical analysis

Descriptive statistics were reported as mean (standard deviation [SD]) for approximately normally distributed variables, and as median (interquartile range) for skewed variables, based on the Shapiro-Wilk test, visual inspection, and distributional characteristics. Paired comparisons between planning techniques (IMRT vs. VMAT) and breathing modes (FB vs. DIBH) were performed using either the paired t-test or the Wilcoxon signed-rank test, as appropriate. To facilitate interpretation of differences in means, all variables were also presented as mean (SD), including those with skewed distributions.

A linear mixed-effects model was applied to evaluate the independent effects of planning technique and breathing mode, with each patient modelled as a random intercept and technique and breathing mode included as fixed effects. Due to the absence of viable transformation for some skewed variables, all outcomes were analysed using parametric assumptions. Analysing skewed variables without transformation is a potential limitation; however, this approach was maintained to ensure a consistent analytical framework across all dosimetric parameters. Model coefficients and 95% confidence intervals (CIs) were reported for each outcome. To account for multiple comparisons across 38 dosimetric parameters, a Bonferroni-adjusted significance threshold of $p < 0.001$ was applied. All analyses were conducted using Stata v19 (StataCorp, College Station, TX, USA).

Ethical considerations

The study adhered to the Declaration of Helsinki and received approval from the St Vincent's Hospital Human Research Ethics Committee (2022/ETH00247), which waived the requirement for informed consent for this anonymised retrospective analysis.

Results

Treatment planning data from 32 patients were analysed. Table 1 summarises the paired dosimetric comparisons between IMRT and VMAT, and between DIBH and FB, across all key planning parameters, including target coverage and selected OAR metrics. Figures S1–S3 display representative coronal, sagittal, and axial isodose distributions for a single patient across the four planning conditions: VMAT-FB, VMAT-DIBH, IMRT-FB, and IMRT-DIBH. The images demonstrate the differences in dose conformality, hotspot location, and the impact of breathing mode on normal tissue expansion.

Target coverage and dose homogeneity

All plans achieved the prescribed dose to the whole breast target, but VMAT plans demonstrated better coverage and homogeneity than IMRT plans. Under FB conditions, VMAT provided near-complete coverage

Table 1 Paired comparisons of dosimetric parameters between IMRT and VMAT techniques under DIBH and FB conditions ($n = 32$)

Parameter	IMRT DIBH	IMRT FB	VMAT DIBH	VMAT FB	*p*-value			
					VMAT versus IMRT (DIBH)	VMAT versus IMRT (FB)	DIBH versus FB (IMRT)	DIBH versus FB (VMAT)
PTV40, volume (cc), mean (SD)	–	–	1075.8 (498.9)	1046.1 (482.1)	–	–	–	0.013
PTV40, volume at 105% (%), median (IQR)	0.0 (0.0–0.1)	0.0 (0.0–0.1)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.004	0.018	0.941	0.124
PTV40, volume at 95% (%), median (IQR)	92.2 (90.6–94.6)	93.4 (91.7–94.9)	99.5 (99.0–99.7)	99.5 (99.2–99.7)	**< 0.001**	**< 0.001**	0.115	0.217
PTV40, volume at 50% (%), median (IQR)	100.0 (100.0–100.0)	100.0 (99.8–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	**< 0.001**	**< 0.001**	0.615	1.000
PTV40, dose at 0.03 cc (Gy), median (IQR)	42.2 (42.0–42.4)	42.1 (42.0–42.4)	41.9 (41.7–42.2)	42.0 (41.8–42.2)	0.015	0.094	0.879	0.286
PTV40 - mean dose (Gy), median (IQR)	39.7 (39.7–39.9)	39.8 (39.7–39.9)	39.9 (39.9–39.9)	39.9 (39.9–40.0)	**< 0.001**	**< 0.001**	0.857	0.032
PTV40, Conformity Index, mean (SD)	1.08 (0.04)	1.10 (0.05)	1.05 (0.02)	1.06 (0.02)	0.035	0.006	0.061	0.101
PTV40, Homogeneity Index, median (IQR)	0.11 (0.11–0.12)	0.10 (0.10–0.12)	0.06 (0.05–0.07)	0.06 (0.05–0.06)	**< 0.001**	**< 0.001**	0.539	0.937
Heart, volume (cc), mean (SD)	–	–	616.4 (122.6)	635.6 (124.4)	–	–	–	0.187
Heart, volume at 20 Gy (%), median (IQR)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.750	0.250	0.250	0.750
Heart, volume at 42 Gy (%), median (IQR)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.750	0.250	0.250	0.750
Heart, mean dose (Gy), median (IQR)	0.4 (0.3–0.5)	0.40 (0.4–0.4)	0.7 (0.7–0.9)	0.8 (0.7–1.0)	**< 0.001**	**< 0.001**	0.103	**< 0.001**
Right lung, volume (cc), mean (SD)	–	–	2308.2 (380.8)	1601.0 (327.4)	–	–	–	**< 0.001**
Right lung, volume at 20 Gy (%), mean (SD)	9.7 (3.4)	11.3 (3.4)	11.5 (1.9)	12.7 (2.0)	0.001	0.016	**< 0.001**	**< 0.001**
Right lung, volume at 16 Gy (%), mean (SD)	11.4 (3.7)	13.0 (3.6)	14.4 (2.0)	15.6 (2.1)	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Right lung, volume at 5 Gy (%), mean (SD)	21.8 (4.5)	22.7 (4.3)	29.9 (2.6)	30.5 (2.2)	**< 0.001**	**< 0.001**	0.083	0.170
Right lung, mean dose (Gy), mean (SD)	5.44 (1.53)	5.76 (1.52)	6.63 (0.64)	6.88 (0.50)	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Left lung, volume (cc), mean (SD)	–	–	1956.5 (368.6)	1321.3 (314.4)	–	–	–	**< 0.001**
Left lung, volume at 5 Gy (%), median (IQR)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.3 (0.1–0.7)	0.3 (0.1–0.6)	**< 0.001**	**< 0.001**	0.484	0.971
Left lung, mean dose (Gy), mean (SD)	0.17 (0.05)	0.16 (0.06)	0.84 (0.24)	0.96 (0.38)	**< 0.001**	**< 0.001**	**< 0.001**	0.014
Lungs, volume at 20 Gy (%), mean (SD)	6.0 (2.7)	6.7 (2.6)	6.3 (1.2)	6.7 (1.1)	**< 0.001**	0.002	**< 0.001**	**0.001**
Lungs, volume at 16 Gy (%), mean (SD)	6.9 (2.9)	7.6 (2.8)	7.8 (1.3)	8.3 (1.1)	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Lungs, volume at 5 Gy (%), mean (SD)	12.7 (3.3)	12.6 (3.3)	16.5 (1.5)	16.5 (1.5)	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Lungs, total mean dose (Gy), mean (SD)	3.0 (0.9)	3.2 (0.9)	4.0 (0.5)	4.2 (0.5)	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Right breast, volume (cc), mean (SD)	–	–	1052.2 (503.7)	997.8 (478.2)	–	–	–	**< 0.001**
Left breast, volume (cc), mean (SD)	–	–	1149.1 (689.5)	1035.4 (586.0)	–	–	–	0.002
Left breast, volume at 4 Gy (%), median (IQR)	0.1 (0–1.1)	0 (0–0.8)	3.7 (3.0–4.3)	4.0 (3.1–4.6)	**< 0.001**	**< 0.001**	0.016	0.067
Left breast, dose at 0.03 cc (Gy), median (IQR)	5.3 (2.5–7.6)	3.3 (2.0–6.8)	12.0 (8.9–16.1)	11.9 (9.1–17.1)	**< 0.001**	**< 0.001**	0.008	0.609
Left breast, mean dose (Gy), mean (SD)	0.3 (0.2)	0.3 (0.2)	1.3 (0.3)	1.2 (0.3)	**< 0.001**	**< 0.001**	0.003	0.916
Spinal cord, dose at 0.03 cc (Gy), median (IQR)	0.3 (0.2–0.3)	0.2 (0.2–0.3)	1.5 (1.3–1.9)	1.5 (1.1–1.9)	**< 0.001**	**< 0.001**	0.229	0.681
Liver, volume (cc), mean (SD)	–	–	1116.2 (406.4)	1168.7 (307.7)	–	–	–	0.320
Liver, dose at 2 cc (Gy), median (IQR)	2.7 (1.6–5.0)	16.5 (5.3–30.1)	3.0 (1.9–6.2)	13.3 (8.0–24.9)	0.329	0.002	**< 0.001**	**< 0.001**
Liver, volume at 5 Gy (%), median (IQR)	0 (0–1.0)	3.2 (0.2–4.5)	0.1 (0–0.7)	7.2 (1.0–11.3)	0.193	**< 0.001**	**< 0.001**	**< 0.001**
Liver, volume at 35 Gy (%), median (IQR)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.813	0.014	0.006	0.033
LAD, volume (cc), mean (SD)	–	–	2.43 (0.65)	2.73 (0.67)	–	–	–	0.002
LAD, volume at 15 Gy (%), median (IQR)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	1.000	1.000	1.000	1.000
LAD, volume at 25 Gy (%), median (IQR)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	1.000	1.000	1.000	1.000
LAD, maximum dose (Gy), median (IQR)	0.3 (0.3–0.4)	0.4 (0.3–0.4)	1.1 (0.9–2.0)	1.9 (1.2–2.8)	**< 0.001**	**< 0.001**	0.005	0.002

Abbreviations: *cc* cubic centimetre, *DIBH* Deep inspiration breath hold, *FB* Free breathing, *Gy* Gray, *IMRT* Intensity-modulated radiation therapy, *IQR* Interquartile range, *LAD* Left anterior descending artery, *PTV* Planning target volume, *SD* Standard deviation, *VMAT* Volumetric modulated arc therapy

Note: Statistically significant results ($p<0.001$) are shown in bold

of the PTV (median PTV V95% 99.5%, interquartile range [IQR] 99.2–99.7), significantly higher than that of IMRT-FB plans (median 93.4%, IQR 91.7–94.9) (pairwise comparison $p < 0.001$) (Fig. 1A). Using DIBH did not compromise target coverage for either technique: IMRT-DIBH had a median PTV V95% of 92.2% (IQR 90.6–94.6), statistically similar to IMRT-FB (pairwise comparison $p = 0.115$), and the corresponding value for VMAT-DIBH was 99.5% (IQR 99.0–99.7) (pairwise comparison with VMAT-FB $p = 0.217$).

The volume of PTV receiving doses above the prescription (hotspots) was minimal with VMAT. The median PTV V105% (volume receiving > 105% of dose) was 0.00% (IQR 0.00–0.01) for VMAT-FB and VMAT-DIBH, compared to small but non-zero hotspot volumes in IMRT plans (median 0.02% for both IMRT-FB and IMRT-DIBH). The differences between VMAT and IMRT were non-significant for FB and DIBH conditions (pairwise $p = 0.018$ and $p = 0.004$ respectively).

Under DIBH condition, the near-maximum PTV dose (D0.03 cc) was slightly lower with VMAT (median 41.9 Gy, IQR 41.7–42.2) compared to IMRT (median 42.2 Gy, IQR 42.0–42.4), although this difference did not reach statistical significance ($p = 0.015$). Breathing mode did not significantly affect this measure of hotspot: IMRT-FB and IMRT-DIBH yielded comparable D0.03 cc values ($p = 0.879$), as did VMAT-FB vs. VMAT-DIBH ($p = 0.286$).

The conformity index and homogeneity index were compared across the four planning techniques. The mean (SD) conformity index was 1.08 (0.04) for IMRT DIBH, 1.10 (0.05) for IMRT FB, 1.05 (0.02) for VMAT DIBH, and 1.06 (0.02) for VMAT FB. Lower conformity index values were observed with VMAT plans compared to IMRT, with statistically significant differences for both DIBH ($p = 0.035$) and FB ($p = 0.006$). The homogeneity index, reported as median (IQR), were 0.11 (0.11–0.12) for IMRT DIBH, 0.10 (0.10–0.12) for IMRT FB, 0.06 (0.05–0.07) for VMAT DIBH, and 0.06 (0.05–0.06) for VMAT FB. Pairwise comparisons showed significantly lower homogeneity index values with VMAT compared to IMRT under both DIBH and FB conditions ($p < 0.001$ for both).

Heart and left anterior descending artery doses

Across all planning techniques and breathing conditions, the heart received negligible high-dose exposure (heart V20 and V42 were 0% in all cases), with no observed differences between IMRT and VMAT or between DIBH and FB (all $p > 0.050$).

In contrast, mean heart dose varied notably across techniques. IMRT consistently resulted in lower median mean heart dose compared to VMAT. Under FB conditions, IMRT-FB delivered a median of 0.4 Gy (IQR 0.4–0.4), whereas VMAT-FB plans yielded 0.8 Gy (IQR 0.7–1.0), representing a statistically significant increase ($p < 0.001$). Similarly, under DIBH, VMAT-DIBH resulted in a higher mean heart dose (median 0.7 Gy, IQR 0.7–0.9) compared to IMRT-DIBH (median 0.4 Gy, IQR 0.3–0.5; $p < 0.001$). However, within-technique comparisons showed no significant difference between FB and DIBH for IMRT ($p = 0.103$), and only a modest reduction for VMAT ($p < 0.001$). These findings are illustrated in Fig. 1B.

LAD V15 and V25 were 0 cc across all plans. Although absolute differences were small, VMAT was associated with higher LAD Dmax than IMRT under both FB and DIBH (VMAT-FB: 1.9 Gy vs. IMRT-FB: 0.4 Gy;

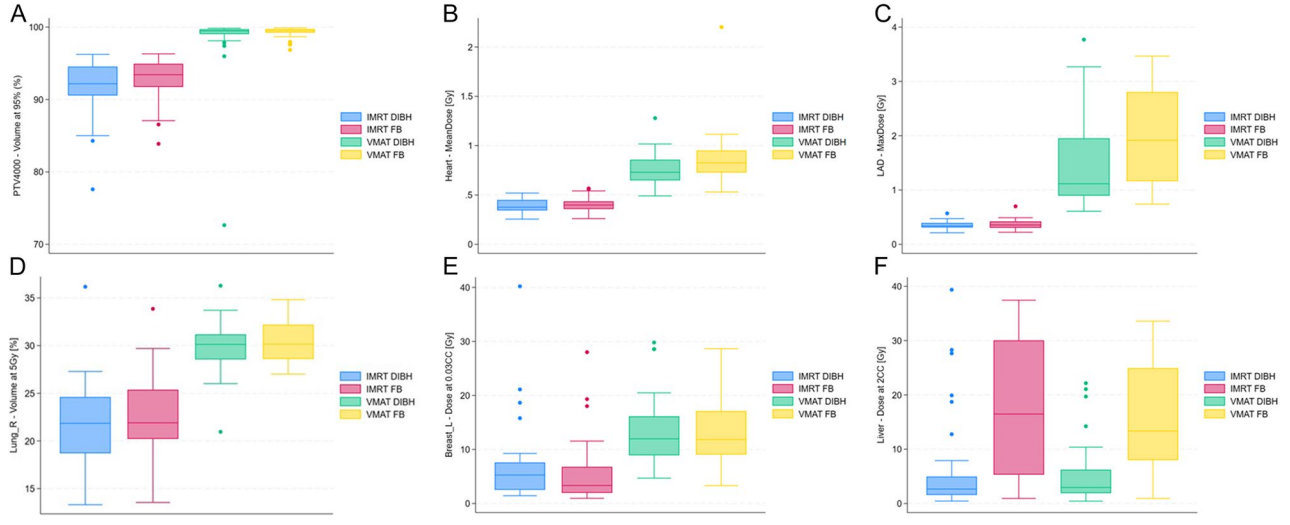


Fig. 1 Boxplots illustrating six key dosimetric parameters across four planning scenarios: IMRT-FB, IMRT-DIBH, VMAT-FB, and VMAT-DIBH. Panels display: (**A**) PTV V95%, (**B**) mean heart dose, (**C**) LAD Dmax, (**D**) right lung V5, (**E**) left breast D0.03 cc, (**F**) liver D2cc. Boxes represent IQR, whiskers indicate 1.5×IQR, and outliers are shown as individual points. Median values are indicated with horizontal lines

VMAT-DIBH: 1.1 Gy vs. IMRT-DIBH: 0.3 Gy; both $p < 0.001$), as illustrated in Fig. 1C. Although LAD Dmax was slightly lower with DIBH, the differences did not remain significant for IMRT or VMAT.

Right lung dose

Radiation exposure to the right lung showed notable differences between techniques and breathing modes. Under FB, the mean right lung V5 (volume receiving ≥5 Gy) was 30.5% for VMAT and 22.7% for IMRT ($p < 0.001$). Under DIBH, V5 was 29.9% for VMAT and 21.8% for IMRT ($p < 0.001$) (Fig. 1D). These findings confirm that VMAT consistently results in a broader low-dose bath than IMRT, irrespective of breathing mode. DIBH reduced right lung V5 slightly within each technique (IMRT: from 22.7% to 21.8%, VMAT: from 30.5% to 29.9%), but the differences were not statistically significant ($p = 0.083$ and 0.170, respectively).

In contrast, DIBH significantly reduced higher-dose metrics (V16 and V20) for both techniques. For IMRT, the mean right lung V20 decreased from 11.3% to 9.7% ($p < 0.001$); for VMAT, V20 was reduced from 12.7% to 11.5% ($p < 0.001$). IMRT-DIBH achieved the lowest mean V20 (9.7%). Similar trends were observed for V16, with significant reductions under DIBH and consistently higher volumes irradiated with VMAT than with IMRT across both breathing conditions. The mean right lung dose followed the same pattern, significantly reduced with DIBH ($p < 0.001$) and consistently higher in VMAT than IMRT ($p < 0.001$).

Left lung dose

The left lung received negligible dose across all plans. IMRT resulted in virtually 0% of the left lung receiving ≥5 Gy, while VMAT-FB plans showed a small but measurable dose (median V5 0.3%, IQR 0.1–0.6). DIBH did not significantly alter V5 for VMAT ($p = 0.971$). However, VMAT significantly increased the mean left lung dose compared to IMRT under both breathing conditions ($p < 0.001$). Under DIBH, the mean dose was 0.84 Gy with VMAT versus 0.17 Gy with IMRT; under FB, 0.96 Gy versus 0.16 Gy, respectively, although the absolute differences were small.

Table 2 Average monitor units and beam-on time by radiotherapy techniques and breathing methods ($n = 32$)

Radiotherapy technique and breath hold	Average total monitor units	Average beam-on time, minute
IMRT-FB	573	3.4
IMRT-DIBH	593	3.5
VMAT-FB	729	4.4
VMAT-DIBH	738	4.6

Abbreviations: *IMRT-DIBH* Intensity-Modulated Radiation Therapy – Deep Inspiration Breath Hold, *IMRT-FB* Intensity-Modulated Radiation Therapy – Free Breathing, *VMAT-DIBH* Volumetric Modulated Arc Therapy – Deep Inspiration Breath Hold, *VMAT-FB* Volumetric Modulated Arc Therapy – Free Breathing

Left breast dose

VMAT was consistently associated with greater left breast exposure compared to IMRT. Under FB, the median V4 was 4.0% for VMAT versus 0% for IMRT ($p < 0.001$). DIBH yielded a modest reduction in VMAT V4 (3.7–4.0%), but this was not statistically significant ($p = 0.067$). Median D0.03 cc was also significantly higher with VMAT under both FB and DIBH (11.9 Gy vs. 3.3 Gy and 12.0 Gy vs. 5.3 Gy, respectively; both $p < 0.001$) (Fig. 1E). DIBH did not reduce D0.03 cc for VMAT ($p = 0.609$), and although it increased D0.03 cc for IMRT, the change was not significant ($p = 0.008$). Mean dose to the left breast was also higher with VMAT (1.2–1.3 Gy vs. 0.3 Gy; $p < 0.001$ across both breathing modes).

Liver

Liver exposure differed notably between techniques and breathing modes. VMAT-FB was associated with significantly higher low-dose exposure (median V5: 7.2%) compared to IMRT-FB (3.2%, $p < 0.001$), though D2cc was slightly lower for VMAT-FB (13.3 Gy vs. 16.5 Gy), without statistical significance ($p = 0.002$).

DIBH markedly reduced liver dose for both techniques. Median D2cc decreased to 2.7 Gy with IMRT and 3.0 Gy with VMAT (both $p < 0.001$ vs. FB), and V5 dropped to nearly negligible levels. Under DIBH, there were no statistically significant differences between VMAT and IMRT in D2cc, V5, or V35 (all $p > 0.001$). See Fig. 1F for distributions of liver D2cc.

Monitor units and treatment time

Table 2 summarises the average monitor units (MUs) and estimated beam-on times. VMAT plans required more MUs than IMRT (VMAT-FB 729, VMAT-DIBH 738 vs. IMRT-FB 573, IMRT-DIBH 593). VMAT-DIBH had the longest average beam-on time (4.6 min), whereas IMRT-FB had the shortest (3.4 min). These treatment times were derived from average beam-on durations for clinically treated patients on a Varian TrueBeam system and exclude setup or imaging time.

Independent effects of technique and breathing mode

The linear mixed-effects model demonstrated independent and statistically significant effects of both planning technique and respiratory management on dosimetric outcomes. Table 3 summarises the independent associations for each factor.

VMAT, when compared to IMRT, was associated with significantly higher exposure to several organs-at-risk, including right lung (V5 + 8.0%, 95%CI: 7.1–8.9%,

Table 3 Linear mixed-effects model evaluating the independent effects of VMAT (versus IMRT) and DBIH (versus FB) on dosimetric parameters ($n = 32$)

Factor	VMAT (versus IMRT)		DIBH (versus FB)	
	Coefficient (95% CI)	***p*-value**	**Coefficient (95% CI)**	***p*-value**
PTV40, volume (cc)	–	–	29.7 (7.7–51.7)	0.008
PTV40, volume at 105% (%)	-0.1 (-0.1–0.0)	0.003	0.0 (0.0–0.0)	0.782
PTV40, volume at 95% (%)	6.6 (5.6–7.5)	**< 0.001**	-0.8 (-1.8–0.1)	0.098
PTV40, volume at 50% (%)	0.4 (0.1–0.7)	0.004	-0.1 (-0.4–0.2)	0.430
PTV40, dose at 0.03 cc (Gy)	-0.2 (-0.4 – -0.1)	0.001	-0.1 (-0.2–0.1)	0.446
PTV40, mean dose (Gy)	0.3 (0.2–0.5)	**< 0.001**	-0.1 (-0.2–0.1)	0.258
PTV40, Conformity Index	-0.02 (-0.03 – -0.01)	0.004	-0.01 (-0.03–0.0)	0.069
PTV40, Homogeneity Index	-0.10 (-0.14 – -0.06)	**< 0.001**	0.01 (-0.03–0.05)	0.494
Heart, volume (cc)	–	–	-19.2 (-47.1–8.7)	0.178
Heart, mean dose (Gy)	0.4 (0.4–0.5)	**< 0.001**	-0.1 (-0.1–0.0)	0.026
Right lung, volume (cc)	–	–	707.2 (635.0 to 779.0)	**< 0.001**
Right lung, volume at 20 Gy (%)	1.5 (0.9–2.2)	**< 0.001**	-1.4 (-2.0 – -0.7)	**< 0.001**
Right lung, volume at 16 Gy (%)	2.8 (2.1 to 3.5)	**< 0.001**	-1.4 (-2.2 – -0.7)	**< 0.001**
Right lung, volume at 5 Gy (%)	8.0 (7.1–8.9)	**< 0.001**	-0.7 (-1.6–0.1)	0.097
Right lung, mean dose (Gy)	1.6 (1.3–1.8)	**< 0.001**	-0.5 (-0.7 – -0.2)	**< 0.001**
Left lung, volume (cc)	–	–	635.2 (565.6–704.8)	**< 0.001**
Left lung, volume at 5 Gy (%)	0.4 (0.3–0.6)	**< 0.001**	-0.019 (-0.2–0.1)	0.788
Left lung, mean dose (Gy)	0.8 (0.7–0.8)	**< 0.001**	0.0 (-0.1–0.0)	0.152
Total lung, volume at 20 Gy (%)	0.7 (0.3–1.0)	**< 0.001**	-1.0 (-1.3 – -0.6)	**< 0.001**
Total lung, volume at 16 Gy (%)	0.9 (0.5–1.3)	**< 0.001**	-1.5 (-1.9 – -1.1)	**< 0.001**
Total lung, volume at 5 Gy (%)	1.9 (1.2–2.7)	**< 0.001**	-3.2 (-4.0 – -2.5)	**< 0.001**
Total lung, mean dose (Gy)	1.2 (1.1–1.3)	**< 0.001**	-0.3 (-0.4 – -0.2)	**< 0.001**
Right breast, volume (cc)	–	–	54.4 (34.3–74.6)	**< 0.001**
Left breast, volume (cc)	–	–	113.7 (49.2–178.2)	0.001
Left breast, mean dose (Gy)	1.1 (1.0–1.2)	**< 0.001**	0.0 (-0.1–0.1)	0.702
Left breast, volume at 4 Gy (%)	3.2 (2.8–3.6)	**< 0.001**	-0.0 (-0.5–0.4)	0.920
Left breast, dose at 0.03 cc (Gy)	7.0 (5.5–8.6)	**< 0.001**	0.9 (-0.7–2.5)	0.278
Spinal cord, dose at 0.03 cc (Gy)	1.4 (1.3–1.6)	**< 0.001**	0.0 (-0.1 to 0.2)	0.862
Liver, volume (cc)	–	–	-52.5 (-154.2–49.2)	0.312
Liver, dose at 2 cc (Gy)	-2.1 (-4.0 – -0.2)	0.032	-10.8 (-12.7 – -8.9)	**< 0.001**
Liver, volume at 5 Gy (%)	1.7 (0.8–2.6)	**< 0.001**	-3.1 (-4.0 – -2.1)	**< 0.001**
Liver, volume at 35 Gy (%)	-0.1 (-0.1 – -0.0)	0.029	-0.0 (-0.1–0.0)	0.588
LAD, volume (cc)	–	–	-0.3 (-0.5 – -0.1)	0.001
LAD, maximum dose (Gy)	1.4 (1.2–1.6)	**< 0.001**	-0.2 (-0.4 – -0.0)	0.037

Abbreviations: *cc* cubic centimetre, *CI* Confidence interval, *DIBH* Deep inspiration breath hold, *FB* Free breathing, *Gy* Gray, *IMRT* Intensity-modulated radiation therapy, *LAD* Left anterior descending artery, *PTV* Planning target volume, *SD* Standard deviation, *VMAT* Volumetric modulated arc therapy

Note: Positive coefficients indicate higher values for VMAT or DIBH relative to reference categories. Statistically significant results ($p<0.001$) are shown in bold

$p < 0.001$; V16 + 2.8%, 95%CI: 2.1–3.5%, $p < 0.001$; V20 + 1.5%, 95%CI: 0.8–2.2%, $p < 0.001$; mean dose 1.6 Gy, 95%CI: 1.3–1.8 Gy, $p < 0.001$), left lung (V5 + 0.4, 95%CI: 0.3–0.6%, $p < 0.001$; mean dose + 0.8 Gy, 95%CI: 0.7–0.8, $p < 0.001$), total lungs (V5 + 1.9%, 95%CI: 1.2–2.7%, $p < 0.001$; V16 + 0.9%, 95%CI: 0.5–1.3%, $p < 0.001$; V20 + 0.7%, 95%CI: 0.3–1.0%, $p < 0.001$; mean dose 1.2 Gy, 95%CI: 1.1–1.3 Gy, $p < 0.001$), heart (mean dose + 0.4 Gy; 95%CI: 0.4–0.5, $p < 0.001$), left breast (D0.03 cc + 7.0 Gy, 95%CI: 0.5–8.6 Gy, $p < 0.001$; V4 + 3.2%, 95%CI: 2.8–3.6%, $p < 0.001$; mean dose 1.1 Gy, 95%CI: 1.0–1.2 Gy, $p < 0.001$), liver (V5 + 1.7%; 95%CI: 0.8–2.6 Gy, $p < 0.001$) and LAD (Dmax 1.4 Gy, 95%CI: 1.2–1.6 Gy, $p < 0.001$), but with increased target coverage (PTV V95% +6.55%; 95%CI: 5.6–7.5, $p < 0.001$), PTV mean dose (+ 0.3 Gy; 95%CI: 0.2–0.5, $p < 0.001$), and lower homogeneity index (-0.1 Gy; 95%CI: -0.2 – -0.1, $p < 0.001$).

DIBH was independently associated with statistically significant reductions in multiple thoracoabdominal dosimetric parameters. These included reductions in right lung V16 (-1.4%, 95%CI: -2.2 – -0.7%, $p < 0.001$), V20 (-1.4%, 95%CI: -2.0 – -0.7, $p < 0.001$), and mean dose (-0.5 Gy, 95%CI: -0.7 – -0.2, $p < 0.001$). Similar reductions were observed for the total lung, including V5 (-3.2%, 95%CI: -4.0 – -2.5%, $p < 0.001$), V16 (-1.5%, 95%CI: -1.9 – -1.1%, $p < 0.001$), V20 (-1.0%; 95%CI: -1.3 – -0.6,

$p < 0.001$), and mean dose (-0.3 Gy, 95%CI: -0.4 – -0.2 Gy, $p < 0.001$). In the liver, DIBH significantly reduced both V5 (-3.1%, 95%CI: -4.0 – -2.1; $p < 0.001$) and D2cc (-10.8 Gy, 95%CI: -12.7 – -8.9; $p < 0.001$). DIBH was associated with significant increases in right lung, left lung, and right breast volumes (all $p \leq 0.001$), consistent with expected thoracic expansion during deep inspiration.

Additional analyses

Additional data are provided in the Appendices: total lung and spinal cord dose metrics (Appendix 1), anatomical volume changes with DIBH (Appendix 2; Table S1, Figures S4A–H), and absolute pairwise differences in dosimetric means (Appendix 3; Tables S2–S5).

Discussion

This dosimetric study compared IMRT and VMAT techniques, with and without DIBH, for right-sided early-stage breast cancer treated with WBI. The findings demonstrate important trade-offs in the selection of advanced radiotherapy techniques. Consistent with previous literature, VMAT provided improved PTV coverage and superior dose homogeneity compared to IMRT, which may be advantageous in patients with complex target geometry [13, 14]. However, this came at the cost of increased exposure to some OARs. Meanwhile, the use of DIBH consistently reduced OAR doses, particularly to the right lung and liver, in both IMRT and VMAT plans.

The integration of DIBH has become increasingly recognised for mitigating OAR exposure during breast radiotherapy [21, 22]. While prior studies demonstrated cardiac sparing with DIBH in right-sided VMAT involving nodal targets [14], our findings in WBI show that mean heart doses were consistently low (< 1 Gy) across all techniques, well below thresholds associated with clinically meaningful cardiac risks [21–23]. Although VMAT resulted in slightly higher heart doses than IMRT, and DIBH provided a small numerical reduction (0.8 Gy to 0.7 Gy), these absolute differences are unlikely to translate into measurable clinical differences. Accordingly, heart dose variations in this setting should be interpreted primarily in the context of dosimetric optimisation, rather than as predictors of toxicity. In right-sided WBI, the principal clinical value of DIBH therefore lies in modest dose reductions to other thoracoabdominal organs, particularly the liver and lungs, rather than additional cardiac sparing, noting that the absolute doses remained well below conventional toxicity thresholds (e.g., right lung V20 < 13%).

While DIBH was associated with reductions in right lung V16, V20, and mean dose, these findings must be interpreted in the context of lung expansion and density reduction during inspiration. Conventional DVH metrics describe the distribution of dose within a volume, but do not directly capture mass-weighted or absolute absorbed lung dose [24]. Consequently, improvements in DVH parameters may partly reflect dose redistribution over a larger lung volume rather than a true reduction in total absorbed energy. This distinction is particularly relevant in right-sided WBI, where baseline lung doses are already modest and the additional patient effort required for DIBH must be carefully justified. Furthermore, regarding clinical implementation, the adoption of DIBH requires increased resources. DIBH necessitates longer scheduled treatment slots to accommodate setup, coaching, and verification. These “time sinks” must be factored into the cost-benefit analysis when weighing the modest dosimetric gains of DIBH for right-sided WBI against department throughput.

Within this context of overall low absolute doses, liver dose reduction is another noteworthy advantage of DIBH, particularly in patients with inferior tumour locations. Our study showed that DIBH was significantly associated with reduced median liver D2cc in both IMRT and VMAT settings, consistent with findings from prior studies using 3DCRT, IMRT, and VMAT techniques [9, 15, 17, 18, 25]. While the liver is not traditionally prioritised during breast radiotherapy, subclinical liver toxicity remains a theoretical concern, especially in patients with prior or planned hepatotoxic treatments.

VMAT was consistently associated with increased low-dose exposure to contralateral organs, including the left breast and lung. Our findings are concordant with prior reports, highlighting the trade-off between improved target conformity and greater integral dose [26–29]. Secondary malignancy risk remains a concern, particularly in younger patients or those with longer life expectancy [26–29]. Importantly, DIBH had limited impact in reducing low-dose exposure. However, the observed increase in low-dose exposure with VMAT should be interpreted in the context of the specific planning approach evaluated in this study. The VMAT plans were generated using a single arc configuration adapted from an institutional breast-and-nodal template and optimised within a single treatment planning system. Low-dose irradiation with VMAT is known to be highly sensitive to arc geometry, collimator settings, and optimisation strategy [30–32]. Alternative configurations, such as butterfly-style arcs or strict avoidance sectors [33], were not explored and may yield different results. Accordingly, our findings should be interpreted as reflective of the evaluated VMAT implementation rather than as an intrinsic property of VMAT across all planning strategies.

An unexpected finding was a non-significant increase in left breast D0.03 cc with DIBH in IMRT plans, possibly reflecting anatomical changes during inspiration, such as breast expansion or altered hotspot distribution due to chest wall motion. This observation reinforces the need

for careful plan evaluation when adopting DIBH, particularly in patients with large or pendulous breasts.

Linear mixed-effects analyses confirmed that VMAT and DIBH independently affected OAR dosimetry. While VMAT improved target metrics, it resulted in higher doses to the heart, lung, liver, and left breast. DIBH independently reduced high-dose lung and liver metrics, without compromising PTV coverage. These findings support a tailored approach to planning, balancing the technical strengths of each modality against patient-specific anatomy, risk factors, and compliance with breath-hold.

Our study has several limitations. As a retrospective planning analysis, it does not account for clinical outcomes such as toxicity or cosmesis. Plan-specific dosimetric verification and formal robustness assessment were not undertaken for this planning cohort, and deliverability was inferred from established institutional quality-assurance experience with similar breast IMRT and VMAT techniques. Additionally, reported treatment times are specific to the Varian TrueBeam system and should not be generalised to newer platforms (e.g., Halcyon) where VMAT delivery may be faster than IMRT. Furthermore, the study evaluated a single VMAT configuration adapted from our institutional breast-and-nodal template. Alternative arrangements, such as butterfly-style VMAT or IMRT designed to more closely mimic tangential fields, were not explored and may further reduce contralateral exposure [6, 12, 34]. Future work should compare different VMAT arc configurations using robust optimisation and verification strategies. Breath-hold compliance was not quantitatively assessed, although all patients had completed clinical DIBH acquisition and CT simulation. Moreover, we did not investigate long-term implications such as second cancer risk, which would require dedicated prediction modelling or cohort follow-up. Finally, regarding statistical methodology, the estimates for highly skewed parameters should be interpreted with caution because of the use of parametric mixed models without transformation.

Nonetheless, the study offers a comprehensive and methodologically rigorous comparison of four clinically relevant planning strategies. The inclusion of both FB and DIBH settings, across IMRT and VMAT, provides novel insight into the dosimetric trade-offs in right-sided WBI without nodal targets—a scenario not well-represented in existing literature.

Conclusion

VMAT achieved superior target coverage and dose homogeneity compared with IMRT, while DIBH consistently reduced lung and liver DVH parameters. However, these findings are specific to the institutional planning approach and delivery technology implemented. The dosimetric benefit of DIBH in right-sided WBI must be weighed against the additional patient burden, particularly when baseline doses are already low. Planning decisions should remain individualised, as statistically significant differences in low-dose exposure may not always correspond to clinically meaningful changes in long-term outcomes. Future studies focusing on correlating these potential dosimetric advantages with long-term clinical outcomes are needed.

Supplementary Information

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Supplementary Material 1
Supplementary Material 2
Supplementary Material 3
Supplementary Material 4
Supplementary Material 5
Supplementary Material 6
Supplementary Material 7
Supplementary Material 8
Supplementary Material 9
Supplementary Material 10
Supplementary Material 11
Supplementary Material 12

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Authors' contributions

Margaret Cokelek (MCk) and Michael Chao (MC) conceived the project and designed the study, and Shing Fung Lee (SFL) drafted the initial manuscript. MCk, Kaj Bayley (KB), Paul Moorfoot (PM), Sophie Le-Nguen (SLN), and Chloe Phung (CP) contributed to treatment planning, data acquisition, and interpretation. Mark Tacey (MT) provided statistical oversight and contributed to data analysis and interpretation. MC supervised the project, contributed to study design and interpretation, and provided critical revisions. All authors reviewed and approved the final manuscript.

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Data availability

The datasets generated and analysed during the current study are not publicly available due to institutional restrictions and patient privacy considerations but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This retrospective planning study was conducted in accordance with institutional guidelines, national research ethics requirements, and the principles of the Declaration of Helsinki. Ethical approval was obtained from the St Vincent's Hospital Human Research Ethics Committee (Reference No.: 2022/ETH00247). As the study involved only analysis of fully anonymised planning data with no patient contact or intervention, the Committee waived the requirement for informed consent.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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