

Original article

Clinical Impact of Intensity-Modulation Radiation Therapy versus 3D Conformal Radiation Therapy in Breast Cancer Patients: Toxicity and Organ Sparing

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Abstract

Radiotherapy selection in breast cancer depends on multiple clinical and dosimetric factors, as it influences organs at risk and determines both early and late toxicities that may affect long-term outcomes. This study compared intensity-modulated radiotherapy (IMRT) and three-dimensional conformal radiotherapy (3D-CRT) with respect to dosimetric parameters, toxicity profiles, and superficial changes. A retrospective analysis was conducted on 20 patients, with 10 treated using IMRT and 10 using 3D-CRT. Data were analyzed using descriptive statistics; Welch's t-test and Mann-Whitney U test were applied due to the small sample size, while chi-square and Fisher's exact tests were used for categorical variables. Results demonstrated that IMRT significantly reduced ipsilateral lung doses ($p = 0.0023$) and improved planning target volume homogeneity ($p < 0.0001$) compared with 3D-CRT. Delayed toxicity occurred in 20% of IMRT patients versus 80% of 3D-CRT patients ($p = 0.0102$). However, IMRT was associated with higher mean cardiac doses ($p = 0.0254$). These findings highlight the trade-offs between IMRT and 3D-CRT, emphasizing the importance of individualized radiotherapy planning in breast cancer treatment.

Keywords: Breast Cancer, IMRT, 3D-CRT, Dosimetric Parameters, Toxicity.

Introduction

Breast cancer remains the most frequently diagnosed malignancy among women worldwide and continues to be a leading cause of cancer-related mortality, representing a major global public health challenge (1). For patients with early-stage breast cancer, breast-conserving surgery followed by adjuvant radiotherapy has become the standard of care, as it significantly reduces the risk of local recurrence and improves overall survival (2).

Despite its therapeutic benefits, radiotherapy is associated with potential adverse effects on adjacent healthy tissues. Of particular concern is radiation exposure to the heart, which has been linked to an increased risk of cardiovascular complications, including ischemic heart disease (3,5). Advances in radiotherapy techniques, such as intensity-modulated radiotherapy (IMRT), have enhanced the precision of dose delivery, achieved improved homogeneity, and reduced unnecessary exposure to surrounding organs. These improvements have been associated with fewer treatment-related toxicities, including acute skin reactions (4,6,7).

In addition, hypo-fractionated radiotherapy has demonstrated comparable long-term outcomes to conventional fractionation while reducing overall treatment time, thereby improving patient convenience and resource utilization (8). Progress in radiotherapy planning and delivery has also contributed to lowering cardiac exposure, making modern breast cancer treatment safer than earlier approaches (9). The present study aims to compare IMRT and three-dimensional conformal radiotherapy (3D-CRT) in breast cancer patients with respect to dosimetric parameters, toxicity profiles, and cosmetic outcomes, thereby evaluating the relative advantages and limitations of each technique in a regional clinical setting.

Methods

Data sources and study design

This retrospective cohort comparison utilized anonymized clinical and radiation planning data from twenty female breast cancer patients who received adjuvant radiotherapy in a radiation oncology setting at Tripoli Radiotherapy Center, Libya. Patients were divided into two equal groups according to treatment modality: intensity-modulated radiation therapy (IMRT; $n = 10$) and three-dimensional conformal radiation therapy (3D-CRT; $n = 10$). Both groups were carefully matched for tumor stage, type of surgery, and prescribed dose, which explains the limited sample size.

Clinical and dosimetric data

Clinical data were obtained from institutional records and included patient demographics, tumor characteristics, and treatment details. Dosimetric parameters were extracted from treatment planning systems and comprised clinical target volume (CTV) heterogeneity index, planning target volume (PTV) heterogeneity index, mean heart dose, mean ipsilateral lung dose, and other indices relevant to target coverage and organ-at-risk sparing. Documented evaluations of acute toxicity, late toxicity, and cosmetic outcomes from routine follow-up visits were also included.

Variables and outcomes

Collected variables encompassed age, tumor stage, surgery type, laterality, prescribed dose, mean heart dose, mean ipsilateral lung dose, CTV and PTV heterogeneity indices, acute toxicity, late toxicity, and cosmetic outcome. Acute toxicity was standardized into erythema and dysphagia indicators, then summarized as a composite acute symptom score. Late toxicity was categorized as absent, fibrosis, or limitation of movement. Cosmetic outcome was classified as mild, moderate, or severe skin discoloration.

Data cleaning and quality assurance

All datasets underwent quality assurance, standardization, and data cleaning procedures to minimize errors and ensure integrity. Column names were standardized, spelling variants harmonized, and stage notation corrected where necessary. Heterogeneity values were extracted from free-text entries. One IMRT ipsilateral lung dose value was inconsistent with the dataset and appeared to represent a decimal-entry error; it was corrected to 894.7 and retained with a data-cleaning flag.

Ethical Statement

This study was conducted in accordance with institutional ethical standards. Approval was obtained from the Ethics Committee of the Faculty of Medicine, International Maaref University (IMU: IRB0326). All procedures performed were consistent with the ethical principles outlined in the Declaration of Helsinki.

Statistical analysis

Continuous variables were summarized using mean, standard deviation, median, interquartile range, minimum, and maximum. Group comparisons for continuous variables were performed using Welch's independent-samples t-test to account for small sample size and potential unequal variance. Mann-Whitney U tests were additionally calculated as non-parametric sensitivity analyses. Categorical variables were summarized in frequency tables and compared using Fisher's exact test for 2×2 tables or Pearson's chi-square test for larger contingency tables. A p-value < 0.05 was considered statistically significant. Given the small sample size, all findings should be interpreted as exploratory rather than definitive.

Results

Table 1 comprised 20 breast cancer patients equally divided between IMRT and 3D-CRT groups. The mean age was lower in the IMRT group (50.6 ± 8.97 years) compared with the 3D-CRT group (60.4 ± 11.30 years). The prescribed dose was identical across both groups, with a mean of 43 Gy. Mean heart dose values showed narrower variability in the IMRT group (578.88 ± 14.06) compared with the wider range observed in the 3D-CRT group (456.72 ± 144.23). Mean ipsilateral lung dose was higher in the 3D-CRT group (1265.48 ± 190.88) relative to IMRT (1001.35 ± 127.17).

CTV heterogeneity index values were slightly lower and more consistent in IMRT (1.05 ± 0.01) compared with 3D-CRT (1.11 ± 0.08). Similarly, PTV heterogeneity index values were lower in IMRT (1.16 ± 0.06) compared with 3D-CRT (1.32 ± 0.07).

Table 1. Descriptive statistics by treatment technique

Variable	Technique	N	Mean $\pm$ SD	Median (IQR)	Minimum	Maximum
Age	IMRT	10	50.60 ± 8.97	47.50 (43.75–58.00)	40.00	66.00
	3D-CRT	10	60.40 ± 11.30	60.50 (52.00–68.75)	43.00	76.00
Dose (Gy)	IMRT	10	43.00 ± 4.83	40.00 (40.00–47.50)	40.00	50.00
	3D-CRT	10	43.00 ± 4.83	40.00 (40.00–47.50)	40.00	50.00
Mean Heart Dose	IMRT	10	578.88 ± 14.06	580.85 (571.45–588.23)	557.90	598.10
	3D-CRT	10	456.72 ± 144.23	496.25 (377.80–577.77)	162.70	589.20
Mean Ipsilateral Lung Dose	IMRT	10	1001.35 ± 127.17	951.35 (902.25–1078.55)	873.10	1213.90
	3D-CRT	10	1265.48 ± 190.88	1318.15 (1234.05–1371.88)	873.80	1513.70
CTV Heterogeneity	IMRT	9	1.05 ± 0.01	1.05 (1.04–1.06)	1.03	1.07
	3D-CRT	10	1.11 ± 0.08	1.08 (1.07–1.09)	1.06	1.29
PTV Heterogeneity	IMRT	10	1.16 ± 0.06	1.15 (1.12–1.18)	1.09	1.29
	3D-CRT	10	1.32 ± 0.07	1.31 (1.27–1.35)	1.24	1.47

Table 2 summarizes comparative means and statistical test results between IMRT and 3D-CRT groups. The mean age was lower in the IMRT group (50.60 years) compared with the 3D-CRT group (60.40 years). Mean heart dose was higher in IMRT (578.88) than in 3D-CRT (456.72). Mean ipsilateral lung dose was lower in IMRT (1001.35) compared with 3D-CRT (1265.48). CTV heterogeneity index values were smaller in IMRT (1.05) compared with 3D-CRT (1.11). PTV heterogeneity index values were also lower in IMRT (1.16) compared with 3D-CRT (1.32). Acute symptom scores were similar between groups (1.20 vs. 1.40). Cosmetic severity scores were lower in IMRT (1.50) compared with 3D-CRT (2.50).

Table 2. Comparative Statistics of IMRT versus 3D-CRT in Breast Cancer Patients

Variable	IMRT Mean	3D-CRT Mean	Mean Diff	CI Low	CI High	Welch t	df	p value	MW U	MW p
Age	50.60	60.40	-9.80	-19.42	-0.18	-2.15	17.12	0.046	24.00	0.053
Mean Heart Dose	578.88	456.72	122.16	18.79	225.53	2.67	9.17	0.025	77.00	0.045
Mean Ipsilateral Lung Dose	1001.35	1265.48	-264.13	-418.15	-110.11	-3.64	15.67	0.002	13.00	0.006
CTV Heterogeneity	1.05	1.11	-0.06	-0.12	-0.01	-2.45	9.56	0.035	3.50	0.001
PTV Heterogeneity	1.16	1.32	-0.16	-0.22	-0.10	-5.71	17.70	<0.001	4.00	0.001
Acute Symptom Score	1.20	1.40	-0.20	-0.64	0.24	-0.95	17.31	0.356	40.00	0.366
Cosmetic Severity Score	1.50	2.50	-1.00	-1.59	-0.41	-3.59	16.64	0.002	15.00	0.005

Table 3 presents categorical comparisons between IMRT and 3D-CRT groups using Fisher's exact test and Pearson's chi-square test. Surgery type showed no difference (Fisher exact statistic = 1.00, $p = 1.00$). Stage distribution was identical across groups (chi-square = 0.000, $p = 1.00$). Acute category comparison yielded Fisher exact statistic = 2.67 ($p = 0.628$). Late category comparison produced chi-square = 8.80 ($p = 0.012$). Cosmetic severity comparison showed chi-square = 9.17 ($p = 0.010$). Any late toxicity was evaluated with Fisher's exact test (statistic = 0.062, $p = 0.023$). Acute erythema yielded Fisher exact statistic = Infinity ($p = 0.474$). Acute dysphagia showed Fisher exact statistic = 0.167 ($p = 0.170$).

Table 3. Comparative Analysis of Categorical Variables Between IMRT and 3D-CRT in Breast Cancer Patients

Variable	Test	Statistic/Odds ratio	p value
Surgery	Fisher exact	1.00	1.00
Stage	Pearson chi-square	0.000	1.00
Acute Category	Fisher exact	2.67	0.628
Late Category	Pearson chi-square	8.80	0.012
Cosmetic Severity	Pearson chi-square	9.17	0.010
Any Late Toxicity	Fisher exact	0.062	0.023
Acute Erythema	Fisher exact	Infinity	0.474
Acute Dysphagia	Fisher exact	0.167	0.170

Discussion

The comparative analysis between IMRT and 3D-CRT in breast cancer radiotherapy highlights important dosimetric and clinical trade-offs. IMRT demonstrated superior homogeneity in both CTV and PTV indices, consistent with prior reports showing improved dose conformity and reduced hot spots (10). This advantage is particularly relevant in patients with large breast volumes or complex anatomy, where 3D-CRT often struggles to achieve uniform dose distribution (11).

Lung sparing was evident in the IMRT group, with significantly lower mean ipsilateral lung doses compared to 3D-CRT. This finding aligns with recent dosimetric studies confirming that IMRT reduces pulmonary exposure and may lower the risk of radiation pneumonitis (12). However, the higher mean heart dose observed in IMRT patients raises concern, as cardiac toxicity remains a critical determinant of long-term morbidity and mortality in breast cancer survivors (13). Techniques such as deep inspiration breath-hold (DIBH) and prone positioning have been recommended to mitigate this risk, particularly in left-sided breast cancer (14).

Studies from Egypt and neighboring countries have provided valuable insights into IMRT versus 3D-CRT. Ghazy et al. reported that IMRT achieved superior conformity and reduced ipsilateral lung dose, though with slightly higher mean heart dose (10). Elsaid et al. compared IMRT and 3D-CRT in semi-lateral decubitus versus supine positions, showing that IMRT improved target coverage and reduced lung exposure, while positioning strategies further minimized cardiac dose (11). Hussein et al. extended this analysis by including hybrid IMRT and VMAT techniques, demonstrating that advanced modalities combined with breath-hold techniques achieved optimal sparing of both lung and heart (12). These regional studies highlight the growing adoption of IMRT in Middle Eastern and North African oncology centers, where anatomical variations and resource constraints often influence technique selection.

International studies corroborate these findings. Darby et al. established the long-term risk of ischemic heart disease following breast radiotherapy, emphasizing the importance of minimizing mean heart dose regardless of technique (13). European trials have shown that prone positioning and hypofractionated schedules can reduce cardiac exposure, particularly in patients with large breast volumes (14). Randomized multicenter trials, such as those by Pignol et al., demonstrated that IMRT significantly reduces acute skin toxicity compared with conventional radiotherapy, improving patient comfort and compliance (15). Harsolia et al. further confirmed that IMRT decreases acute dermatitis and enhances cosmetic outcomes (16).

Taken together, regional and international evidence supports the conclusion that IMRT provides superior dosimetric quality and reduced lung exposure, while 3D-CRT may offer lower mean heart doses in certain settings. Hybrid approaches and advanced techniques such as DIBH, prone positioning, and adaptive planning are increasingly recommended to balance

these trade-offs (17). Consensus guidelines from ESTRO reinforce the importance of standardized target volume delineation to ensure reproducibility and safety across centers (18).

Conclusion

This study demonstrates that IMRT provides superior target homogeneity and reduced ipsilateral lung exposure compared with 3D-CRT, while 3D-CRT may offer lower mean heart doses. Regional and international evidence supports these findings, highlighting both the benefits and limitations of each technique (10–18). The choice of radiotherapy modality should therefore be individualized, taking into account patient anatomy, tumor laterality, and the need for cardiac sparing. Integration of advanced techniques such as deep inspiration breath-hold, prone positioning, and hybrid planning can further optimize outcomes. Ultimately, careful treatment planning is essential to balance dosimetric advantages with long-term toxicity risks, ensuring improved survivorship and quality of life for breast cancer patients.

Conflict of Interest

The authors declare that there are no conflicts of interest related to this study.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available due to institutional confidentiality policies but are available from the corresponding author upon reasonable request.

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