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Original Research Article

Comparison Between Forward and Inverse Treatment Planning in Breast Cancer Radiotherapy

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Abstract:

Background: Breast cancer radiotherapy requires precise dose delivery to maximize tumor control while minimizing exposure to surrounding organs at risk (OARs). Forward-planned IMRT (FP-IMRT) and inverse-planned IMRT (IP-IMRT) are commonly used techniques with distinct planning approaches.

Aim: To compare FP-IMRT and IP-IMRT in terms of target coverage, dose homogeneity, conformity, hotspot distribution, organ sparing, and overall plan quality in early-stage breast cancer patients.

Methodology: A prospective observational study was conducted on 80 female patients (≤70 years) post-breast-conserving surgery at the Department of Medical Physics, State Cancer Institute, Indira Gandhi Institute of Medical Sciences, Bihar, India, from January 2022 to December 2024. Both FP-IMRT and IP-IMRT plans were generated for each patient using CT-based simulation. Dosimetry parameters, including planning target volume (PTV) coverage, homogeneity index (HI), conformity index (CI), and doses to the heart, ipsilateral lung, and contralateral breast, were analyzed. Statistical comparison was performed using Student's t-test.

Results: IP-IMRT achieved superior PTV coverage (97.2% vs. 94.8%), better homogeneity (HI 0.12 vs. 0.18), higher conformity (CI 0.96 vs. 0.89), fewer hotspots (15% vs. 37.5%), and improved OAR sparing compared to FP-IMRT. Overall plan quality favored IP-IMRT (50% excellent plans vs. 22.5%).

Conclusion: IP-IMRT provides superior dosimetric outcomes in target coverage, homogeneity, conformity, and OAR sparing, while FP-IMRT remains simpler and resource-efficient with reduced low-dose bath; technique selection should be individualized based on patient and institutional factors.

Keywords: Breast cancer, IMRT, forward planning, inverse planning, dosimetry, organ-at-risk.

Introduction

Breast cancer is one of the most common malignancies in women across the globe and it still poses a major burden to the population. Survival rates have increased significantly with the development of screening, early detection, and multimodal treatment approaches. Radiotherapy is one of the treatment modalities that are important in the management of early-stage breast cancer, especially after breast conservation surgery (BCS). The practice of irradiating the whole breast of women who have undergone BCS has long been the norm in cases of early breast cancer (EBC) [1]. The landmark meta-analysis by the Early Breast Cancer Trialists Collaborative Group (EBCTCG) has strongly supported this approach by showing significant improvements in local control and overall survival, thus providing the basis of adjuvant radiotherapy in breast-conserving treatment.

Radiotherapy methods have experienced significant development over the last several decades, as the necessity to enhance the therapeutic effects and reduce the toxicity of the treatment process has been present [2]. First, the traditional two-dimensional (2D) radiotherapy methods with wedge filters were commonly used. These methods were however constrained by low dose conformity and lack of ability to precisely spare adjacent normal tissues. This led to the development and adoption of three-dimensional conformal radiotherapy (3D CRT), which allowed for better visualization of target volumes and critical organs using computed tomography (CT)-based planning [3]. In spite of these advances, 3D CRT continues to have some limitations, especially dose inhomogeneity in the target volume. The presence of hotspots can result in increased normal tissue toxicity, even though acceptable local control rates are achieved.

To address these shortcomings, newer radiotherapy methods have been developed, which aim at improving dose conformity and homogeneity and minimizing exposure to organs at risk (OARs). Of these, intensity-modulated radiation therapy (IMRT) has become a major breakthrough in the radiotherapy of breast cancer. IMRT allows the radiation beam intensity to be modulated with high precision, which allows highly conformal dose distributions that are very similar to the shape of the target volume. This leads to better dose homogeneity in the breast and less radiation to the surrounding normal tissues like the heart and lungs. Moreover, IMRT allows the intensification of treatment using methods like simultaneous integrated boost (SIB), which allows the selective increase of dose to the tumor bed without a significant increase in toxicity [4].

There are two principal approaches used for developing IMRT treatment plans. The first approach is forward-planned IMRT, commonly referred to as the field-in-field technique. In this method, the medical physicist manually designs and adjusts treatment fields based on visual evaluation of dose distribution using beam's eye view projections. Subfields are created within the primary radiation fields to reduce dose inhomogeneity and minimize hotspots while ensuring adequate target coverage. Forward planning is relatively simple, cost-effective, and less time-consuming; however, its effectiveness largely depends on the planner's experience and expertise. Additionally, this technique may be less suitable for patients with complex anatomy or irregular target volumes, where achieving optimal dose conformity can be challenging.

Conversely, inverse planning IMRT is a more advanced, computer-optimized method whereby desired dose goals and constraints of the target volume and OARs are predetermined [5]. Optimization algorithms are then applied to the treatment plan in treatment planning system to identify the optimal beam parameters, such as the number, direction, shape, and weight of radiation beams, to meet the desired objectives. This method enables high dose conformity and sparing of critical structures than forward planning. Inverse planning is also automated, which minimizes inter-planner variability and increases reproducibility. Nevertheless, it needs sophisticated software, more time to plan, and a selection of optimization parameters to prevent unintended dose distributions.

Besides the development of new planning methods, technological developments like respiratory gating (RG) have also enhanced the safety and effectiveness of radiotherapy of breast cancer. One of the most widely used RG techniques is deep inspiration breath hold (DIBH), which has been particularly beneficial in left-sided breast cancer [6]. When breathing in, the diaphragm becomes flatter and the lungs are enlarged, which increases the space between the breast tissue and vital organs like the heart and left anterior descending coronary artery (LADCA). DIBH can greatly minimize radiation exposure to these organs by providing radiation at this stage. A number of studies have shown that DIBH is capable of reducing the dose to the heart and ipsilateral lung relative to free-breathing methods, thus minimizing the risk of cardiovascular complications in the long term [7].

Despite the availability of multiple advanced radiotherapy techniques, there remains ongoing debate regarding the optimal planning approach for breast cancer treatment. Both forward and inverse IMRT techniques have their own advantages and limitations in terms of dose distribution, treatment efficiency, planning complexity, and resource utilization. While forward planning is simpler and more cost-effective, inverse planning offers greater precision and consistency. Therefore, a systematic comparison of these two techniques is essential to determine their relative efficacy and clinical applicability in breast cancer radiotherapy.

In this context, the present study aims to compare forward and inverse treatment planning techniques in breast cancer radiotherapy, with a focus on evaluating target coverage, dose homogeneity, conformity, and sparing of organs at risk. Such a comparison is expected to provide valuable insights into optimizing treatment planning strategies and improving therapeutic outcomes for patients undergoing breast cancer radiotherapy.

Methodology

Study Design: This study was a prospective observational comparative study designed to evaluate and compare forward planning and inverse treatment planning techniques in breast cancer radiotherapy with respect to target coverage and organ-at-risk (OAR) sparing.

Study Area: The study was conducted in the Department of Medical Physics, State Cancer Institute

Indira Gandhi Institute of Medical Sciences, Bihar, India.

Study Duration: The study was carried out over a period of two years from January 2022 to December 2024.

Study Participants

Inclusion Criteria

- Female patients diagnosed with early-stage breast cancer
- Who underwent breast-conserving surgery (BCS)
- Age ≤ 70 years
- ECOG performance status 0–1
- Patients suitable for radiotherapy planning and treatment
- Patients able to maintain stable positioning during simulation

Exclusion Criteria

- Patients with metastatic breast cancer
- Prior history of thoracic radiotherapy
- With severe comorbid conditions affecting treatment tolerance
- Pregnant or lactating women
- Unable to undergo CT simulation or immobilization procedures
- With incomplete clinical or imaging data

Sample Size: A total of 80 patients meeting the inclusion criteria were included in the study.

Procedure: All eligible patients underwent CT simulation after proper counseling regarding the procedure. Patients were immobilized in a supine position using appropriate immobilization devices, with both arms elevated above the head to ensure reproducibility. Radio-opaque markers were placed over the surgical scar and anatomical landmarks to facilitate accurate localization. CT simulation was performed using a GE CT Simulator (GE Revolution EVV). CT images were acquired with a slice thickness of 2.5 mm for the thoracic region under free-breathing conditions.

The acquired CT images were transferred to the treatment planning system (TPS), and target volumes along with organs at risk (OARs) were delineated according to standard Radiation Therapy Oncology Group (RTOG) guidelines. The clinical target volume (CTV) included the visible breast tissue and lumpectomy cavity, while the planning target volume (PTV) was generated by adding appropriate margins, excluding the superficial skin layer to avoid dose buildup effects. OARs such as the heart, ipsilateral lung, contralateral breast, and liver were contoured carefully.

A prescribed dose of 40 Gy in 15 fractions and boost with 12.5 Gy in 5 fractions was delivered to the planning target volume (PTV) as per institutional protocol. Treatment planning was performed on a non-contrast CT dataset. Treatment planning was carried out using the Eclipse Treatment Planning System (Varian Medical Systems), version 16.1.0.

Table 1: Treatment Planning System and Algorithms

S. No.	Calculation Type	Algorithm	Version
1	Volume Dose Calculation	Anisotropic Analytical Algorithm (AAA)	16.1.0
2	DVH Estimation	DVH Estimation Algorithm	16.1.0
3	Portal Do se Prediction	Portal Dose Image Prediction (PDIP)	16.1.0
4	Optimization	Photon Optimizer (PO)	16.1.0
5	Surface Compensation	Irregular Surface Compensator (ISC)	16.1.0

For each patient, two separate radiotherapy treatment plans were generated: forward planning (FP-IMRT) and inverse planning (IP-IMRT).

In forward planning (FP-IMRT), conventional opposite tangential beams were used. Subfields were manually created using multileaf collimators (MLC) to reduce dose inhomogeneity and hotspots. Beam weights, field arrangements, and dose normalization points were iteratively adjusted based on dose distribution to achieve optimal plan quality and adequate target coverage.

In inverse planning (IP-IMRT), intensity-modulated radiotherapy (IMRT) plans were generated using multiple beam angles (typically 5–7 fields). Optimization algorithms were applied by defining dose constraints for the PTV and OARs. The plans were refined iteratively to achieve improved target coverage while minimizing radiation exposure to surrounding normal tissues.

Treatment was delivered using a TrueBeam SVC linear accelerator (Varian Medical Systems). Patient setup verification was performed using an onboard imaging system with Cone Beam CT (CBCT).

Dose-volume histograms (DVHs) were generated for both planning techniques. Dosimetric parameters including homogeneity index (HI), conformity index (CI), and doses to OARs were evaluated and compared. The homogeneity index (HI) was calculated using the formula (D2% – D98%)/D50%, indicating dose uniformity within the target volume, while the conformity index (CI) assessed how well the prescribed dose conformed to the target volume.

Statistical Analysis: All collected data were entered into Microsoft Excel and analyzed using Statistical Package for the Social Sciences (SPSS) version 27.0. Descriptive statistics were used to summarize patient characteristics and dosimetry parameters. Continuous variables were expressed as mean ± standard deviation. Comparative analysis between forward and inverse planning techniques was performed using the student's t-test. A p-value of <0.05 was considered statistically significant.

Result

Table 1 presents the demographic characteristics of the study participants (n = 80). The age distribution shows that the majority of patients belonged to the 31–45 years age group (35%), followed by those aged 46–60 years (30%). Participants aged ≤30 years and >60 years each constituted an equal proportion of the study population (17.5% each). This indicates that middle-aged individuals formed the predominant group in the study. Regarding laterality, a slightly higher proportion of cases involved the left breast (52.5%) compared to the right breast (47.5%), suggesting a marginal predominance of left-sided breast involvement among the participants.

Table 2: Demographic Characteristics of Study Participants (n = 80)

Variable	Frequency (n)	Percentage (%)
Age Group (years)		
≤30	14	17.5
31–45	28	35
46–60	24	30
>60	14	17.5
Laterality		
Left Breast	42	52.5
Right Breast	38	47.5

Table 2 shows the comparison of target coverage parameters between FP-IMRT and IP-IMRT among 80 patients. The mean PTV coverage was higher in IP-IMRT (97.2 ± 1.8%) compared to FP-IMRT (94.8 ± 2.6%), and this difference was statistically significant (p = 0.001), indicating better target dose coverage with inverse planning. Similarly, the Homogeneity Index (HI) was lower in IP-IMRT (0.12 ± 0.03) than in FP-IMRT (0.18 ± 0.04), with a highly significant difference (p = 0.0005), suggesting more uniform dose distribution in IP-IMRT. In addition, the Conformity Index (CI) was also improved in IP-IMRT (0.96 ± 0.03) compared to FP-IMRT (0.89 ± 0.05), and this difference was statistically significant (p = 0.0008), reflsecting better conformity of radiation dose to the target volume. Overall, IP-IMRT demonstrated superior performance over FP-IMRT in terms of target coverage, dose homogeneity, and conformity.

Table 3: Comparison of Target Coverage Parameters Between FP-IMRT and IP-IMRT (n = 80)

Parameter	FP-IMRT (Mean ± SD)	IP-IMRT (Mean ± SD)	p-value
PTV Coverage (%)	94.8 ± 2.6	97.2 ± 1.8	0.001
Homogeneity Index (HI)	0.18 ± 0.04	0.12 ± 0.03	0.0005
Conformity Index (CI)	0.89 ± 0.05	0.96 ± 0.03	0.0008

Table 3 presents the dose received by organs at risk (OARs) among the study population (n = 80) for both forward-planned IMRT (FP-IMRT) and inverse-planned IMRT (IP-IMRT). The findings demonstrate that IP-IMRT achieved significantly lower radiation exposure to critical structures compared to FP-IMRT. The mean heart dose was reduced from 6.5 ± 1.2 Gy in FP-IMRT to 4.2 ± 0.9 Gy in IP-IMRT, which was statistically significant (p = 0.002). Similarly, the ipsilateral lung V20 was lower in IP-IMRT (24.1 ± 2.8%) compared to FP-IMRT (28.4 ± 3.5%), with a significant difference (p = 0.003). Additionally, the dose to the contralateral breast was reduced from 3.1 ± 0.7 Gy in FP-IMRT to 2.2 ± 0.5 Gy in IP-IMRT, also showing statistical significance (p = 0.005). Overall, these results indicate that IP-IMRT provides superior sparing of organs at risk compared to FP-IMRT.

Table 4: Dose to Organs at Risk (OARs) (n = 80)

Organ at Risk	FP-IMRT (Mean ± SD)	IP-IMRT (Mean ± SD)	p-value
Heart Mean Dose (Gy)	6.5 ± 1.2	4.2 ± 0.9	0.002
Ipsilateral Lung V20 (%)	28.4 ± 3.5	24.1 ± 2.8	0.003
Contralateral Breast Dose (Gy)	3.1 ± 0.7	2.2 ± 0.5	0.005

Table 4 shows the comparison of hotspot distribution, defined as regions receiving doses greater than 110%, between forward-planned IMRT (FP-IMRT) and inverse-planned IMRT (IP-IMRT) in 80 patients. The table indicates that hotspots were present in 30 patients (37.5%) treated with FP-IMRT, whereas only 12 patients (15%) in the IP-IMRT group experienced hotspots. Conversely, the absence of hotspots was higher in IP-IMRT, with 68 patients (85%) showing no hotspots compared to 50 patients (62.5%) in the FP-IMRT group. This suggests that IP-IMRT provides better dose homogeneity, reducing the occurrence of regions receiving excessively high doses compared to FP-IMRT.

Table 5: Comparison of Hotspot (Dose >110%) Distribution (n = 80)

Hotspot Presence	FP-IMRT (n)	IP-IMRT (n)	Percentage FP (%)	Percentage IP (%)
Present	30	12	37.5	15
Absent	50	68	62.5	85

The overall plan quality was categorized into Excellent, Good, Acceptable, and Poor based on quantitative dosimetric parameters including PTV coverage, Homogeneity Index (HI), Conformity Index (CI), hotspot presence, and organ-at-risk (OAR) dose constraints.

Plans were classified as Excellent when all major criteria were optimally achieved, defined as PTV coverage ≥95%, HI ≤0.15, CI ≥0.95, hotspot volume (dose >110%) ≤5%, and all OAR doses within recommended tolerance limits. Plans were categorized as Good when minor deviations from optimal criteria were observed, defined as PTV coverage between 92–95%, HI between 0.15–0.20, CI between 0.90–0.95, hotspot volume between 5–10%, and OAR doses within acceptable limits (not exceeding tolerance by more than 1 standard deviation). Plans were considered Acceptable when moderate deviations were present, defined as PTV coverage between 88–92%, HI between 0.20–0.25, CI between 0.85–0.90, hotspot volume between 10–15%, and OAR doses exceeding tolerance limits by up to 2 standard deviations but remaining clinically manageable. Plans were classified as Poor when major dosimetric constraints were not met, defined as PTV coverage <88%, HI >0.25, CI <0.85, hotspot volume >15%, and/or OAR doses exceeding tolerance limits by more than 2 standard deviations. These thresholds were adapted and modified from previously published dosimetric evaluation studies and ICRU recommendations [8].

Table 5 presents the overall plan quality assessment for 80 patients comparing Forward Planning IMRT (FP-IMRT) and Inverse Planning IMRT (IP-IMRT). The results indicate that IP-IMRT achieved a higher proportion of excellent plans, with 40 cases (50%) rated excellent compared to 18 cases (22.5%) in FP-IMRT. While FP-IMRT had more plans rated as good (34 cases, 42.5%) than IP-IMRT (30 cases, 37.5%), it also had a greater number of acceptable (20 vs. 8) and poor-quality plans (8 vs. 2). Overall, IP-IMRT demonstrated superior plan quality, as reflected by a higher percentage of excellent plans and a lower percentage of poor plans compared to FP-IMRT.

Table 6: Overall Plan Quality Assessment (n = 80)

Plan Quality	FP-IMRT (n)	IP-IMRT (n)	Percentage FP (%)	Percentage IP (%)
Excellent	18	40	22.5	50
Good	34	30	42.5	37.5
Acceptable	20	8	25	10
Poor	8	2	10	2.5

Discussion

The current research study which investigates FP-IMRT and IP-IMRT in breast cancer radiation treatment shows that IP-IMRT delivers better target coverage and dose distribution and organ-at-risk protection than FP-IMRT. The research findings correspond with Kestin et al. (2000) [9], who showed that inverse planning methods produced better PTV coverage and higher conformity indices, while IP-IMRT plans showed higher maximum dose levels inside the PTV area together with more consistent dose distribution. FP-IMRT created smaller hotspots together with a decrease in conformal dose coverage, which resulted in a decision between dose distribution at specific points and maximum dose distribution throughout the treatment area, which matches the findings of Al-Rahbi et al. (2013) [10], who observed that FP-IMRT generated smaller hotspot areas but showed minor reductions in PTV conformity. IP-IMRT showed lower homogeneity index results than FP-IMRT, which showed more consistent dose distribution throughout the treated area, whereas the IP-IMRT plans showed better control of dose distribution throughout the treatment area because inverse planning enables precise dose distribution for complex breast tissue.

In the present study, inverse-planned IMRT (IP-IMRT) demonstrated a significantly lower mean heart dose compared to forward-planned IMRT (FP-IMRT), indicating superior cardiac sparing with inverse planning. This finding is consistent with previous studies that highlight the advantage of inverse optimization in achieving better dose conformity and minimizing radiation exposure to critical organs. Boyages and Baker (2018) [11] reported that advanced IMRT techniques improve dose uniformity while requiring careful optimization to reduce cardiac dose. Similarly, Feng et al. (2011) [12] emphasized the importance of minimizing radiation exposure to cardiac structures to reduce long-term cardiovascular complications. Although specific cardiac substructures were not evaluated in the present study, the observed reduction in mean heart dose suggests a clinically relevant benefit of IP-IMRT in reducing cardiac risk.

Lung toxicity remains a central concern in breast radiotherapy. The analysis showed that IP-IMRT plans achieved lower V20 values for the ipsilateral lung while FP-IMRT plans showed decreased V5 measurements. The study Berg et al. (2018) [13] showed that IMRT treatment for breast cancer leads to decreased doses to the ipsilateral lung but results in higher low-dose radiation exposure because of the rising number of monitor units (MUs) that doctors need to use. The present study confirmed this, as IP-IMRT required approximately five times more MUs than FP-IMRT, consistent with Al-Rahbi et al. (2013), which led to higher radiation exposure for nearby organs. The two methods achieved lung sparing results that doctors consider acceptable because they maintained ipsilateral lung V20 values below 20%. The study results showed that FP-IMRT produced lower contralateral lung doses than other methods, which supports the research finding from Stovall et al. (2008) [14] that minimizing low-dose distribution should be a priority for lowering the chances of developing secondary tumors.

Dose to the contralateral breast was another key metric. The study results demonstrated that FP-IMRT delivered lower mean doses which were less than 1 Gy together with reduced V5 results when compared to IP-IMRT. Grantzau and Overgaard (2015) [15] established through their findings that medical professionals need to limit contralateral breast dose in order to decrease second primary breast cancer risk among younger patients. The study results show that medical professionals need to establish precise target coverage together with OAR protection because IP-IMRT techniques create the risk of increasing low-dose radiation to areas outside the treatment zone.

The analysis of hotspot distribution showed that IP-IMRT plans produced less than 110% of the prescribed dose hotspots than FP-IMRT plans. The findings of this study match the results that El-zawawy and Hammoury (2015) [16] reported about inverse planning which improved breast dose distribution by creating uniformity and decreasing high-dose areas outside the treatment target. FP-IMRT generates smaller hotspots in specific areas but creates non-conformal dose distribution patterns which demonstrate to physicians the required balance between reducing hotspot areas and achieving full target coverage when selecting their planning method.

The study demonstrated that IP-IMRT produced better plan results because it generated 50 percent excellent plans and only 2 percent poor-quality plans, while FP-IMRT produced 22.5 percent excellent plans and 10 percent poor plans. Chen et al. (2020) [17] showed that inverse-planned IMRT produces optimized plans which achieve better conformity and homogeneity results, but this method requires more MUs and creates low-dose radiation to adjacent tissues.

The study results demonstrate that IP-IMRT delivers better coverage to PTV areas and maintains dose distribution uniformity while protecting OARs from high radiation doses. FP-IMRT provides less radiation to the heart and opposite breast area while needing fewer MUs. The clinical implication is that inverse planning should be preferred when precise target coverage is paramount whereas forward planning remains valuable for reducing low-dose exposure to sensitive structures. The combination of these findings with previous research demonstrates that treatment results in breast cancer radiotherapy need planning restrictions and patient-specific factors to achieve optimal results.

Conclusion

This study demonstrates that inverse-planned IMRT (IP-IMRT) provides superior dosimetric outcomes compared to forward-planned IMRT (FP-IMRT) in breast cancer radiotherapy. IP-IMRT achieved significantly better target coverage, improved dose homogeneity and conformity, reduced hotspot formation, and enhanced overall plan quality. Furthermore, it showed improved sparing of critical organs at risk, including the heart, ipsilateral lung, and contralateral breast, thereby potentially reducing treatment-related toxicity. However, FP-IMRT remains a simpler and more resource-efficient technique with lower monitor unit requirements and reduced low-dose spread. Therefore, the choice of treatment planning technique should be individualized based on patient anatomy, clinical requirements, and institutional resources to achieve optimal therapeutic outcomes.

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