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Optimizing Quality Assurance in Breast IMRT Treatment Plans: A Comparative Study of Point Dose and 2D Dose Verification

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ABSTRACT

Intensity-Modulated Radiation Therapy (IMRT) requires rigorous dose verification to ensure accurate radiation delivery. This study evaluates point dose verification and 2D dose verification techniques in detecting dose discrepancies due to isocenter shifts in IMRT treatment for post-mastectomy breast cancer cases. Five post-mastectomy breast IMRT plans were retrospectively analyzed, with phantom-based measurements compared against Treatment Planning System (TPS) calculations. The results indicate that point dose verification provides reliable absolute dose measurements, but lacks spatial resolution, whereas 2D verification captures dose variations more effectively. Dose discrepancies remained within acceptable limits for shifts up to ±3 mm, but shifts of ±5 mm or more resulted in clinically significant deviations. Gamma Passing Rates (GPR) decreased substantially beyond ±5 mm shifts, underscoring the importance of precise patient positioning. These findings support the integration of both verification methods to improve IMRT quality assurance, particularly in resource-limited settings. Future advancements in AI-driven dosimetry and real-time in vivo monitoring may further optimize dose verification, enhancing treatment accuracy and patient safety.

INTRODUCTION

Breast cancer remains one of the most significant global health challenges, representing the most frequently diagnosed malignancy among women and a leading cause of cancer-related mortality [1]. According to recent epidemiological studies, breast cancer accounts for approximately 11.6 % of new cancer cases worldwide, with an estimated mortality rate of 6.9 % across both sexes [1]. In Indonesia, the burden of breast cancer is particularly alarming, as it is not only the most commonly diagnosed cancer among women but also the primary cause of cancer-related deaths in this population [2]. Given the increasing incidence of breast cancer, timely and effective treatment strategies are crucial for improving patient outcomes.

Radiotherapy is an essential component of breast cancer management, particularly after mastectomy, where it serves to eradicate residual cancer cells and reduce the risk of local recurrence. Intensity-Modulated Radiation Therapy (IMRT) has emerged as a highly precise conformal radiotherapy technique, offering superior Organ-At-Risk (OAR) sparing compared to conventional Three-Dimensional Conformal Radiotherapy (3DCRT) [3,4]. IMRT achieves this by modulating beam intensity across different regions, ensuring that tumor tissues receive an optimal dose while minimizing exposure to adjacent healthy structures [5,6]. Despite these advantages, IMRT presents significant challenges in treatment planning and delivery, necessitating rigorous Quality Assurance (QA) measures to ensure accurate dose distribution [7,8]. The adoption of IMRT in resource-limited settings, such as local hospitals in Indonesia, is further complicated by a lack of access to advanced verification tools and QA infrastructure, raising concerns about its practical implementation.

One of the most critical challenges in IMRT is the potential for dose deviations due to various factors, including limitations in the Treatment Planning System (TPS) algorithms, mechanical inaccuracies in Multi-Leaf Collimator (MLC)

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settings, and patient-related variables such as organ motion and setup errors [9,10]. Even minor positional shifts can lead to unintended dose variations, potentially compromising treatment efficacy and patient safety [11]. To address these concerns, robust QA protocols have been developed to verify and validate planned versus delivered doses, ensuring treatment accuracy and reliability [12,13].

Dosimetric verification methods play a fundamental role in IMRT QA, with available techniques categorized into single-point dose measurements, Two-Dimensional (2D) dose mapping, and Three-Dimensional (3D) dose verification. Point dose verification, typically performed using ionization chambers, provides a simple yet effective means of assessing dose accuracy at a single location within the treatment field [14]. However, this approach is limited in its ability to capture the full spatial distribution of dose discrepancies. Conversely, 2D dose verification techniques, such as film dosimetry and planar ionization chamber arrays, enable a more comprehensive evaluation of dose distributions, allowing for a more detailed analysis of spatial dose variations [15,16]. The most advanced method, 3D dosimetry, utilizes tools such as Electronic Portal Imaging Devices (EPIDs) and Monte Carlo-based dose reconstruction to provide volumetric dose validation, but its complexity and resource requirements limit widespread adoption in clinical practice [17].

International guidelines established by organizations such as the American Association of Physicists in Medicine (AAPM) provide standardized dose deviation tolerances for IMRT QA, typically allowing for deviations of ±5 % within the target volume and higher tolerances (up to ±10 %) for OARs [18,19]. Ensuring adherence to these guidelines is essential for maintaining treatment accuracy, particularly in settings where access to sophisticated QA tools is restricted. However, existing QA frameworks often require adaptation to accommodate the specific needs of different clinical environments, highlighting the need for tailored verification strategies.

Despite significant advancements in IMRT QA methodologies, local hospitals in Indonesia and other resource-limited settings struggle with limited access to the necessary verification equipment, leading to suboptimal implementation of IMRT. The primary concern is whether the current verification techniques can effectively detect and quantify dose deviations due to isocenter shifts, particularly when using simplified QA tools. The lack of confidence in available QA methods hinders the broader adoption of IMRT, necessitating a reevaluation of verification strategies.

Previous studies have suggested that 2D dose verification methods provide a more comprehensive assessment of dose discrepancies than single-point measurements. For instance, research comparing ionization chamber-based point dose verification with 2D detector arrays found that planar dosimetry techniques are more sensitive to spatial dose variations and can better detect discrepancies arising from setup errors and isocenter shifts [9,15]. However, further research is needed to evaluate the clinical significance of these findings in breast cancer IMRT plans, particularly in scenarios where access to high-end verification systems is limited.

This study aims to evaluate the ability and sensitivity of point dose verification and 2D verification in detecting dose discrepancies between planned and delivered IMRT doses due to isocenter shifts. By systematically assessing the impact of positional variations on dose distribution, this research seeks to establish a more reliable and feasible QA approach for breast cancer IMRT in resource-limited clinical settings. The novelty of this study lies in its comparative analysis of point dose and 2D verification methods within a constrained-resource environment, providing valuable insights into the practical implementation of IMRT QA in such settings. Furthermore, the study's findings will contribute to the ongoing refinement of IMRT verification protocols, potentially informing future guideline adaptations to enhance treatment accuracy and patient safety.

METHODOLOGY

The IMRT treatment plans were developed for post-mastectomy breast cancer cases, utilizing a dynamic IMRT delivery approach. Five IMRT treatment plans were designed, each incorporating five gantry angles set at 30°, 110°, 140°, 300°, and 330°, with collimator angles fixed at 0°. The prescribed dose for all treatment plans was 50 Gy, administered in 25 fractions. The planning process was conducted using the Monaco TPS software version 5.11.03 (Elekta AB, Stockholm, Sweden), which employs Monte Carlo algorithms for accurate dose calculation. Monte Carlo simulations are widely acknowledged for their superior accuracy in modeling dose distributions and handling tissue inhomogeneities, making them a preferred choice for IMRT QA [15,20,21].

To conduct the verification procedures, a water slab phantom with a PTW TM 30013 Farmer

ionization chamber detector (PTW Freiburg, Germany) was utilized. The phantom, measuring 30 x 30 x 10 cm³, was scanned using a Siemens CT Scanner (Siemens Healthineers, Germany) to generate Digital Imaging and Communications in Medicine (DICOM) files, which were then imported into the TPS. The ionization chamber detector was positioned at a depth of 5 cm from the surface of the phantom, aligning precisely with the isocenter determined by the intersection of midline, right lateral, and left lateral laser beams. The field size was set to 10 cm x 10 cm, with a Source-to-Axis Distance (SAD) of 100 cm, ensuring consistent measurement conditions.

The Quality Assurance (QA) plan was developed by replicating the beam configurations of the clinical IMRT plans onto the phantom setup. The isocenter was carefully aligned, and the Monte Carlo algorithm in the TPS was used to compute the expected dose distribution. Dose Volume Histograms (DVH) were generated to provide statistical insights into mean, maximum, and minimum doses across the treatment volume. The computational time varied depending on the Monitor Unit (MU) values assigned to each plan, with higher MU values necessitating longer processing times.

Point dose verification was performed using the Farmer ionization chamber detector to measure absolute dose values at the true isocenter point in the phantom. The same scanning setup was maintained to ensure consistency. The detector reading, expressed in nano Coulombs (nC), was converted into absorbed dose following the guidelines of the International Atomic Energy Agency (IAEA) Technical Reports Series No. 398 (TRS-398). The absorbed dose was calculated using Eq. (1) as follows.

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0} \quad (1)$$

Where $D_{w,Q}$ is the absorbed dose at the slab phantom at the reference point (Gy), M_Q is the detector reading from the measurement (nC), N_{D,w,Q_0} is the calibration factor (Gy/nC), and k_{Q,Q_0} is the correction factor between the reference condition (Q_0) and the measurement condition (Q).

The percentage dose difference between TPS and measured dose at the true isocenter point was determined using Eq. (2) as follows.

$$\Delta D(\%) = \frac{D_M - D_{TPS}}{D_P} \times 100\ \% \quad (2)$$

Where ΔD is the dose difference expressed in percentage, D_M is the measured dose, D_{TPS} is the calculated dose from the TPS, and D_P is the prescribed dose. The dose difference tolerance was 3 % [22].

To assess the impact of isocenter shifts on dose delivery, controlled displacements of the phantom were performed in three QA plans. The phantom was shifted by ±3 mm, ±5 mm, and ±10 mm along the x-axis, simulating common setup variations encountered in clinical settings. For the isocenter shifting, the doses measured at the shifted isocenter point ($D_{shifted}$) were compared to the doses measured at the true isocenter point (D_{true}), using Eq. (3).

$$\Delta D(\%) = \left|\frac{D_{shifted} - D_{true}}{D_{true}}\right| \times 100\ \% \quad (3)$$

A critical component of this study was the implementation of 2D dose verification using the PTW Octavius 729 planar detector (PTW Freiburg, Germany). The detector was positioned at a depth of 5 cm from the phantom surface, maintaining a total depth of 10 cm, which included the 2 cm thickness of the detector holder. The Surface-to-Source Distance (SSD) was adjusted to 95 cm to align with the treatment setup. The phantom and detector were scanned using the Siemens CT simulator, and the resulting images were imported into the TPS to establish a QA plan.

The dose distribution for each IMRT plan was computed within the TPS, generating dose maps that were subsequently validated against actual measurements. The 2D dose verification was performed using a 6 MV photon beam with a 10 x 10 cm² field from the Elekta Synergy linear accelerator (Elekta AB, Stockholm, Sweden). The recorded dose maps were analyzed using PTW VeriSoft software (PTW Freiburg, Germany), applying gamma analysis with criteria of 3 % dose difference and 3 mm Distance-To-Agreement (DTA). The Gamma Passing Rate (GPR) was required to meet or exceed 90 % for verification to be considered acceptable. Additionally, the effect of isocenter shifts on dose distribution was evaluated by shifting the isocenter by ±3 mm, ±5 mm, and ±10 mm along the x-axis. The dose maps from these shifted positions were compared against the reference isocenter position, and corresponding GPR values were recorded to assess the impact of displacement on treatment accuracy.

The importance of robust verification protocols in IMRT cannot be overstated, particularly

in mitigating errors associated with isocenter shifts and patient positioning [8,23]. By integrating both point dose and 2D verification techniques, this study seeks to provide a comprehensive assessment of dose discrepancies and their implications for breast cancer IMRT treatment. The findings are expected to inform future QA protocols, improving treatment reliability and optimizing patient safety in clinical settings.

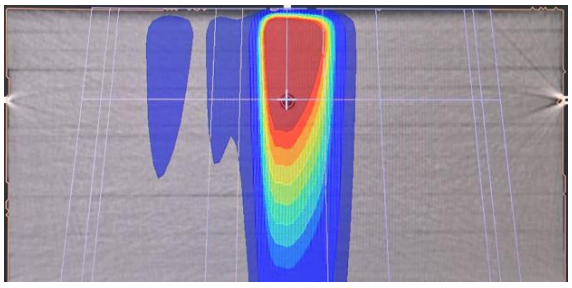
RESULTS

Point dose verification

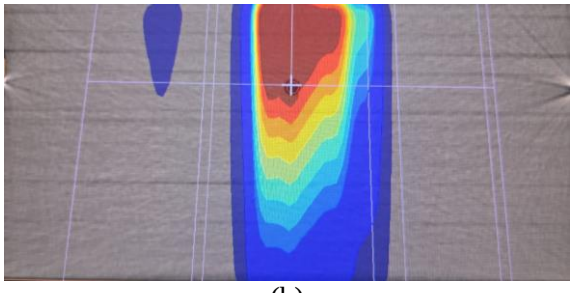
Point dose verification was performed by measuring the absolute dose at the isocenter point using an ionization chamber. The comparison between the measured and calculated doses is presented in Table 1. The results indicate that the dose differences in all plans were within the clinically acceptable tolerance of 3 %. Figure 1 shows the dose distribution of two QA plans (Plan 2 and Plan 5).

Table 1. The comparison between the measured and the calculated dose at the true isocenter point.

Plan	MU	D_M (Gy)	D_{TPS} (Gy)	ΔD (%)
1	688.84	2.282	2.265	0.86
2	736.55	2.300	2.250	2.52
3	708.59	2.239	2.210	1.45
4	696.21	2.319	2.265	2.71
5	833.32	2.251	2.273	-1.11



(a)



(b)

Fig. 1. The dose distribution of a) plan 2 and b) plan 5. The isodose levels from the inner line (dark red) to the outer line (purple) are 2.1 Gy, 2.0 Gy, 1.9 Gy, 1.8 Gy, 1.7 Gy, 1.6 Gy, 1.5 Gy, 1.4 Gy, 0.985 Gy, and 0.67 Gy.

These results emphasize the importance of accurate isocenter localization, as positioning uncertainties can significantly impact the delivered dose. The placement of the ionization chamber detector plays a vital role in obtaining reliable dose measurements, with literature suggesting that chamber orientation and alignment with the treatment volume can influence accuracy [7,24]. Furthermore, Monte Carlo-based TPS calculations have shown superior accuracy in predicting dose distributions, with reported deviations within 1-3 % compared to actual measured doses [25,26].

Dose deviation due to isocenter shifts

The impact of isocenter shifts on dose accuracy was evaluated by shifting the phantom's position along the x-axis by ±3 mm, ±5 mm, and ±10 mm. The dose differences between shifted and true isocenter positions are illustrated in Fig. 2. A shift of ±10 mm resulted in dose deviations exceeding the 3 % tolerance in all three plans, except for plan 3 at a 10 mm (positive x-axis) shift, which is still below the 3 % tolerance. Similarly, a 5 mm shift in the negative x-axis direction caused unacceptable discrepancies in Plan 3, reinforcing the critical need for precise patient positioning. Conversely, isocenter shifts of ±3 mm remained within acceptable tolerance limits, suggesting that minor positional variations may not significantly impact dose accuracy in low-dose gradient regions.

These findings align with prior research, which establishes ±3 mm as the threshold for acceptable isocenter displacement in IMRT [14]. Deviations beyond this limit can lead to dose misadministration, affecting both tumor coverage and Organ-At-Risk (OAR) sparing [5]. The clinical implications of exceeding isocenter shift tolerances include inadequate tumor dose coverage and increased OAR exposure, potentially leading to treatment failure and heightened toxicity risks [27,28]. Advanced imaging techniques, such as Cone Beam Computed Tomography (CBCT) and Electronic Portal Imaging Devices (EPIDs), have been proposed as effective strategies for real-time isocenter verification to mitigate these discrepancies [29,30].

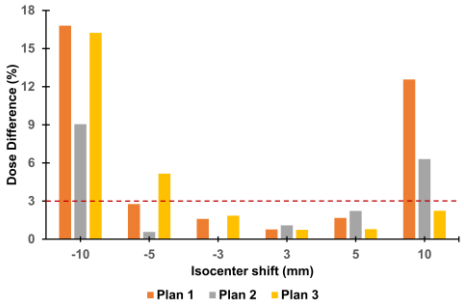


Fig. 2. Dose deviation due to isocenter shifts in three breast IMRT plans. The dashed red line indicates 3 % tolerance of the dose difference tolerance.

2D dose verification

Two-dimensional dose verification was performed using the PTW Octavius 729 planar detector, and the Gamma Passing Rate (GPR) was assessed under various isocenter shift conditions. The GPR for each plan at the true isocenter is shown in Table 2, and the change of the GPR due to isocenter shifts is shown in Table 3. The results indicate that all plans met the required GPR threshold of ≥90 % at the true isocenter position. However, a shift of ±10 mm resulted in a significant GPR reduction to approximately 40 % in most plans, indicating substantial dose discrepancies. Similarly, a ±5 mm shift led to a GPR of about 60 %, except for Plan 2 at -5 mm and Plan 3 at 5 mm, which exhibited a slightly higher GPR of around 70 %.

Table 2. GPR of five breast IMRT plans at the true isocenter point.

Plan	MU	GPR (%)
1	688.84	99.8
2	736.55	98.4
3	708.59	90.0
4	696.21	97.4
5	833.32	98.2

Table 3. The GPR of three IMRT plans at the true and shifted isocenter position.

Isocenter shift (mm)	GPR (%)		
	Plan 1	Plan 2	Plan 3
-10	38.2	45.4	40.6
-5	61.8	72.5	54.0
-3	91.6	93.8	65.9
0*	99.8	98.4	90.0
3	83.1	82.1	88.3
5	56.3	60.8	75.7
10	33.9	40.2	39.7

*no shift (true isocenter point)

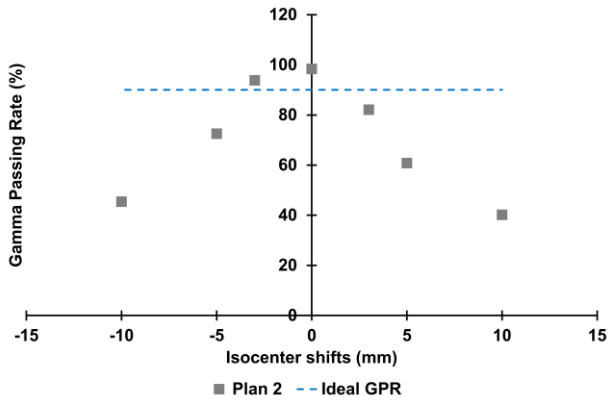


Fig. 3. Change in GPR value of plan 2 due to isocenter shifts. The dashed blue line indicates the required GPR (i.e., 90 %) value in the IMRT QA.

Figure 3 shows the change in GPR value of plan 2 due to isocenter shifts. The different shift directions result in different GPR values. For this plan, even a 3 mm shift in the +x direction causes the GPR drop below 90 %. This indicates that the isocenter position influences the severity of the isocenter shift effects on the GPR value.

These findings confirm that 2D dose verification is highly sensitive to positional shifts, capturing spatial dose variations that may be overlooked by single-point dose measurements. Studies have demonstrated that planar detectors provide superior spatial resolution compared to ionization chambers, making them more effective for detecting dose inhomogeneities [9,31]. The PTW Octavius 729 has been validated in previous research as a reliable tool for IMRT quality assurance, achieving high GPRs under stringent acceptance criteria [9,31].

The choice of gamma evaluation criteria also plays a critical role in assessing IMRT QA results. The commonly used 3 %/3 mm criterion tends to yield higher pass rates compared to the more stringent 2 %/2 mm criterion, which increases sensitivity to minor dose discrepancies [6,32]. The results of this study indicate that stricter gamma evaluation criteria may be required for plans involving high-dose gradient regions to ensure treatment accuracy [33]. This aligns with findings from prior studies that emphasize the necessity of adapting verification criteria based on treatment complexity and anatomical considerations [19,34].

DISCUSSION

Ensuring precise dose delivery in breast Intensity-Modulated Radiation Therapy (IMRT) is critical for optimizing therapeutic outcomes while minimizing exposure to Organs-At-Risk (OARs). This study comprehensively evaluates the effectiveness of point dose verification and 2D dose verification in detecting dose discrepancies due to isocenter shifts. The findings confirm that integrating these verification methods enhances the robustness of Quality Assurance (QA) in breast IMRT.

The results demonstrate that both point dose verification and 2D dose verification contribute uniquely to the QA process. Point dose verification, performed using an ionization chamber, provides accurate absolute dose measurements at critical locations, ensuring that the delivered dose closely matches the prescribed plan. However, this method lacks the ability to capture spatial dose variations across the treatment

field. Conversely, 2D dose verification enables a comprehensive assessment of dose distribution across a plane, identifying potential discrepancies caused by positioning errors or variations in beam modulation [14,35]. The synergy between these techniques ensures a higher degree of confidence in IMRT dose delivery, particularly in treatment plans with complex dose gradients.

The data from this study further reinforces the notion that 2D verification methods are more sensitive to spatial dose deviations. This is evidenced by the significant reduction in Gamma Passing Rates (GPR) observed with isocenter shifts of 5 mm or greater, while point dose verification remained within tolerance limits in some cases. These findings align with previous research, which indicates that 2D dosimetry provides superior insights into discrepancies that could otherwise be overlooked in single-point measurements [29,36]. This highlights the necessity of implementing multi-tiered QA protocols in breast IMRT to ensure the highest levels of treatment accuracy and patient safety.

One of the key challenges in the widespread adoption of IMRT in resource-limited hospitals is the availability of sophisticated QA equipment. The findings suggest that incorporating 2D dosimetry alongside point dose verification can provide an effective and feasible QA strategy without requiring extensive resources. By utilizing simpler but reliable verification tools such as ionization chambers and planar detectors, hospitals with limited budgets can still achieve high-quality treatment standards [15].

The integration of cost-effective QA methodologies in clinical workflows also facilitates the standardization of IMRT verification procedures. Simplified yet rigorous protocols enable more accessible training programs for medical physicists, reducing inter-institutional variations in treatment delivery. Additionally, hospitals with constrained resources can benefit from collaborative QA initiatives that leverage shared expertise and standardized verification guidelines. These approaches align with global efforts to enhance IMRT accessibility and ensure equitable cancer treatment across diverse healthcare settings [24].

The findings of this study are consistent with existing literature emphasizing the advantages of 2D dose verification over single-point measurements in breast IMRT QA. Previous research has demonstrated that while point dose verification provides critical absolute dose data, it lacks the spatial resolution necessary to detect complex dose variations. Studies by Sumida et al. (2016) and Pardo et al. (2016) support this conclusion, highlighting the need for a combination of dosimetric techniques to ensure comprehensive treatment validation [29,36].

Furthermore, the study corroborates earlier findings that isocenter shifts beyond ±3 mm can lead to clinically significant dose discrepancies. The observed dose deviations in this study align with research indicating that shifts of ±5 mm or greater result in dose variations exceeding the recommended 3 % tolerance, which could impact tumor control and OAR protection [5,9]. These findings underscore the necessity for precise patient positioning and advanced verification tools to mitigate the risks associated with setup errors.

The use of Monte Carlo-based TPS calculations in this study also supports previous evidence that Monte Carlo algorithms provide higher accuracy in dose prediction compared to conventional algorithms. Studies by Jäkel et al. (2019) and Tài et al. (2019) have demonstrated that Monte Carlo-based TPS calculations achieve relative dose deviations within 1-3 % of measured values, further validating their utility in IMRT QA [25,26]. While Monte Carlo methods require substantial computational resources, their accuracy in predicting dose distributions makes them an invaluable tool for IMRT verification in both research and clinical settings. Open source Monte Carlo user code, such as BEAMnrc, could be used as an independent QA tool for pre-treatment verification of IMRT plans, by comparing the simulated dose distribution with the TPS calculation and measurement [21,37].

Emerging advancements in dosimetric verification are expected to further improve the accuracy and efficiency of breast IMRT QA. One of the most promising developments is the integration of Artificial Intelligence (AI) and machine learning algorithms into dosimetric analysis. AI-driven models have the potential to enhance dose prediction accuracy, streamline QA processes, and identify treatment plan anomalies in real time. Studies have indicated that machine learning algorithms can significantly reduce QA workload while maintaining high precision in dose verification [16,38].

Advancements in Electronic Portal Imaging Devices (EPIDs) and 3D dosimetric systems are also expected to revolutionize IMRT QA [22]. EPIDs have been increasingly utilized for in vivo dose verification, offering real-time feedback on treatment accuracy. Future developments in EPID technology, including enhanced resolution and improved calibration techniques, may provide even greater accuracy in dose measurement and spatial verification [39,40]. Additionally, 3D dosimetric systems that incorporate deformable phantoms and volumetric dose

reconstruction are expected to improve spatial resolution in QA assessments, offering a more holistic approach to treatment validation [9].

Another key area of future research is the refinement of gamma evaluation criteria for IMRT QA. While the 3 %/3 mm criterion remains a widely accepted standard, recent studies suggest that a stricter 2 %/2 mm criterion may be necessary for treatment plans involving high-dose gradient regions [6,32]. Adapting verification criteria based on treatment complexity and anatomical considerations will enhance the precision of IMRT QA protocols, ensuring that dose discrepancies are detected with greater sensitivity [33].

The integration of advanced dosimetric verification methods, AI-driven QA processes, and emerging imaging technologies holds immense potential for improving breast IMRT treatments. The findings of this study contribute to the growing body of evidence supporting multi-tiered QA approaches, emphasizing the importance of both point dose and 2D verification in ensuring optimal treatment accuracy and patient safety. However, this study only included a limited number of treatment plans, i.e., five plans. Therefore, further investigation using a larger number of plans would be beneficial to extend the findings of this study.

CONCLUSION

This study evaluated the accuracy and sensitivity of point dose verification and 2D dose verification in detecting dose discrepancies in breast IMRT plans due to isocenter shifts. The findings demonstrate that while point dose verification provides precise absolute dose measurements, 2D dose verification offers a more comprehensive assessment of spatial dose distributions, making it a superior method for capturing dose variations caused by positional uncertainties. The results indicate that isocenter shifts of ±3 mm remain within acceptable dose deviation tolerances, whereas shifts beyond ±5 mm can lead to clinically significant discrepancies, emphasizing the importance of precise patient positioning.

The integration of both verification methods enhances IMRT QA, particularly in resource-limited hospitals where access to advanced dosimetric tools is restricted. The study highlights the necessity of refining QA protocols to ensure accurate treatment delivery, suggesting that incorporating machine learning and AI-driven dosimetric analysis may further optimize dose verification. Future research should focus on improving real-time in vivo dosimetry and developing adaptive radiotherapy techniques to mitigate setup uncertainties and enhance treatment outcomes. By strengthening QA methodologies, the reliability and effectiveness of IMRT for breast cancer treatment can be further improved, ultimately benefiting patient care and safety.

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AUTHOR CONTRIBUTION

S. Herwiningsih, J. A. E. Noor, D. Y. B. Munthe, F. K. Hentihu, and C. S. Widodo equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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