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Verification of Breast Cancer Treatment Planning with Various Radiation Techniques Using Monte Carlo Simulations and Linac Log Files

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ABSTRACT

Due to the complexity of radiotherapy techniques, rigorous Patient-Specific Quality Assurance (PSQA) is crucial to ensure the accuracy of treatment plans. This study aims to evaluate the performance of the Treatment Planning System (TPS) by comparing its dose distribution calculations with those obtained from the PRIMO Monte Carlo simulation. Treatment plans for 3D-CRT, IMRT, and VMAT were generated for a Rando breast phantom using the TPS. Subsequently, the dose distributions from the TPS were compared with those obtained from the PRIMO Monte Carlo simulation. Key metrics, including Homogeneity Index (HI) and Conformity Index (CI), were calculated to assess the quality of dose distribution. Furthermore, the dose constraints on OARs were evaluated to assess the impact on surrounding healthy tissues. To further validate the TPS, dose distributions from the linac log file (Dynalog) for VMAT were reconstructed within the PRIMO environment. These reconstructed distributions were then compared with the dose distributions calculated directly by the TPS. Gamma index analysis was employed to evaluate the agreement between these two sets of data. The comparison between TPS and Monte Carlo simulations revealed that 3D-CRT plans exhibited smaller deviations in HI and CI compared to IMRT and VMAT plans. However, a significant improvement in HI and CI values was observed in both IMRT planning simulations and Dynalog VMAT file simulations, indicating enhanced plan quality. The dose received by OARs in all treatment plans remained within the acceptable dose thresholds, demonstrating effective sparing of surrounding healthy tissues. For the PSQA procedure, the 3D-CRT technique is still the safest due to its lower level of complexity compared to IMRT and VMAT. More complex treatments should consider the robustness of treatment transfer information from TPS to linac to avoid dosimetry errors.

INTRODUCTION

Radiation therapy is one of the main methods in breast cancer treatment, which aims to destroy cancer cells while minimizing damage to surrounding healthy tissue. Among the various techniques available, Intensity Modulated Radiotherapy (IMRT), and Volumetric Modulated Arc Therapy (VMAT) are modern approaches that have been widely used. Both techniques offer high flexibility and precision in delivering radiation doses that are appropriate to the shape and position of the tumor, especially in cases of breast cancer that often has a complex anatomical distribution.

The advantages of IMRT and VMAT lie in the ability to set complex parameters, such as multi-leaf collimator (MLC), radiation beam fluence, and configuration on the linear accelerator (linac) head. However, the complexity of this dosimetry planning requires an automated algorithm capable of generating optimal parameters to ensure maximum dose to the tumor without harming the surrounding healthy tissue [1]. As a consequence of the high level of precision, a strict Quality Assurance (QA) procedure is required,

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especially through the Patient Specific Quality Assurance (PSQA) approach, to ensure the accuracy of the dose distribution according to the planning.

PSQA plays an important role in ensuring the concordance between planning and therapy delivery, especially in cases requiring Adaptive Radiotherapy (ART), which is the process of adapting planning due to changes in patient anatomy during the course of therapy [2]. The PSQA procedure is usually performed based on guidelines from the American Association of Physicists in Medicine (AAPM) Task Group No. 218, which recommends tolerance criteria, such as gamma pass rate (GPR) $\geq$ 95 % with dose difference (DD) and distance to agreement (DTA) criteria parameters of 3 %/2 mm and a dose threshold of 10 % [3].

Monte Carlo simulation had been widely used for evaluation of radiation output in both low and high energy photon. Several user code such as BEAMnrc, GEANT, FLUKA, PHITS, and PRIMO showed a good performance to assess radiation output in medical range [4-7]. PRIMO is superior compared other user code because the user-friendly graphical interface, which is easier for evaluating modern radiotherapy. Several studies, such as those conducted by Aamri et al. (2021) and Altuwayrish et al. (2022), showed that PRIMO simulation results are comparable to other TPS systems, with dose distributions still within clinical tolerance limits [8,9]. In addition, PRIMO can also utilize Varian's linac log file called dynalog to analyze the dynamic movement of the device, including the MLC, which contributes to the evaluation of the suitability of therapy planning and implementation [1].

In addition, the accuracy standards recommended by AAPM, such as the Root-Mean-Aquare Error (RMSE) limit of 3.5 mm [10], are considered too loose for certain clinical applications. Some researchers suggest a tighter RMS limit of from 3.3 to 1.0 mm to improve the reliability of modern radiotherapy systems [11,12]. Therefore, re-evaluation of dosimetry parameters using stricter standards is needed to ensure the safety and effectiveness of radiation therapy, especially in breast cancer.

This study aims to reconstruct the planning and verify the dose distribution using PRIMO software on 3D-CRT, IMRT, and VMAT techniques for breast cancer therapy. In addition, this study also evaluates the dose distribution on PRIMO with dynalog linac input to determine the accuracy of the information transfer made by the TPS to the linac machine.

METHODOLOGY

Treatment planning

Female Alderson RANDO Phantom (RSD inc, Canada) was utilized to simulate a left whole breast cancer irradiation. The phantom was planned to be exposed with a Varian iX linac with a 6 MV photon beam. Three techniques, i.e., 3D Conformal Radiation Therapy (3DCRT), IMRT, and VMAT, were used to obtain the dose distribution and the transfer information differences between different complexity plans. Prescribe dose was 5000 cGy to the mean dose for IMRT and VMAT and to the isocenter for 3DCRT. For 3DCRT, two radiation fields were performed with the Field in Field technique. For the IMRT and VMAT, seven radiation fields and two arcs were performed, respectively. MLC and Jaws positions were generated manually for 3DCRT, and automatically for IMRT and VMAT using the optimization algorithm.

All the plans were calculated by using Eclipse ver.13.6 (Varian, Canada) and an Analytical Anisotropic Algorithm (AAA). After the treatment plan was approved. The treatment information, such as CT images, structures, plans, and doses, was exported to DICOM format.

Dynalog file

The treatment plans were transferred to the linac's console for one fraction of 200 cGy in QA mode. To obtain the dynalog file, automatic storage on the linac console needs to be activated. Then, the linac performs irradiation for three variations of techniques. After that, the folder containing the planning data and the dynalog files in ".dlg" format is copied for the Monte Carlo simulation.

Monte Carlo simulation

The Monte Carlo simulation consists of three parts. First, the commissioning of the Monte Carlo to the baseline data of the linac. Second, the simulation of the female RANDO phantom by using the RT-plan input. Third, the simulation of the same phantom with the log-file input.

The commissioning part began with tuning the initial parameters of PRIMO Monte Carlo. The following parameters were: Initial energy: 6.2 MeV, Energy FWHM: 0.186 MeV, Focal spot FWHM: 0.15 cm, Beam divergence: 2.5 degrees.

These parameters are in accordance with the research conducted by Rodriguez [1]. Considering that each linac is unique, the output of the Monte Carlo simulation at the initial parameters is adjusted to the radiation output of the Varian iX linac at our

hospital. In this research, the simulation was divided into two segments. The first segment was the fixed component of the gantry, and the second one was the beam parameter and phantom. The simulation was performed using 10^8 particle histories in the first segment. The results in this segment can be used as input in the second segment.

Monte Carlo simulation on RANDO phantom

Simulations on the RANDO phantom were divided into two categories, i.e., based on the radiotherapy plan (RT-plan) and based on the dynalog after irradiation. Monte Carlo simulations on the RANDO phantom were in the second segment which combine the moving linac parameters like gantry angle, jaws, mlc position, and phantom information. Simulations are carried out with 10^8 particle histories and applying *a coarse dose distribution* to speed up the simulation time. Besides, the simulation applied variance reduction technique of splitting factor of 300 to boost the computation time. Simulations were carried out for each RT-plan and dynalog files, so that each produces a dose distribution.

Evaluation and analysis

The quality of plan and simulation were evaluated by using *the Homogeneity Index* (HI) and *Conformity Index* (CI) for the target volume. For OARs, the evaluation followed the dose constraints for each organ. In this study, the 5 OARs selected based on the highest priority level such as Ipsilateral Lung, Contralateral Lung, Heart, and Spinal Cord [13]. To find the HI value, the Eq. (1) recommended by ICRU 83 was used.

$$\mathrm{HI} = \frac{D_{2\%} - D_{98\%}}{D_{50\%}} \qquad (1)$$

When HI values approaching zero indicate high uniformity of dose distribution in the target volume [14]. Meanwhile, CI values can be obtained from the following Eq. (2).

$$\mathrm{CI} = \frac{Vol_{95\%}Coverage}{Vol_{PTV}} \qquad (2)$$

where $Vol_{95\%}coverage$ is the total volume that receives 95 % of the prescription dose, Vol_{PTV} is the target volume. A value of 1 in the CI represents complete coverage of the prescription dose in the target volume without affecting the surrounding tissue [15].

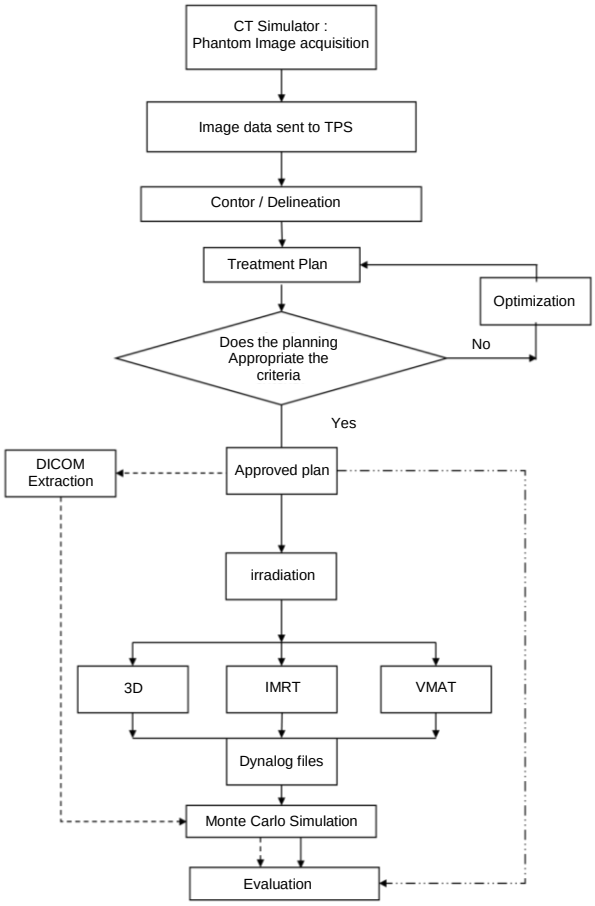

Fig. 1. Research flow diagram. The solid line represents the treatment plan and dynalog file input for Monte Carlo simulation. The dash line represents the Monte Carlo simulation with radiotherapy plan as input. The dash and dot line means the approved dose distribution to evaluate with both Monte Carlo simulation.

In addition, gamma index analysis was performed by comparing the planned dose distribution with the Monte Carlo simulation Monte Carlo simulation was used as a reference in this comparison [16]. The dose distribution evaluation included global gamma pass rate (GPR) values with 3%/3mm criteria and 10 % dose threshold by using the built-in algorithm from PRIMO. The overall research was described in Fig. 1.

RESULTS

Monte Carlo validation

The differences in PDD and beam profile between simulation and measurement results can be seen in Fig. 2. The blue line was the result of the Monte Carlo simulation calculation, while the black line was the baseline data. Visually, their differences were shown at the edge of the beam profile. This could be happened because of the fluctuation of particle deposition on

Monte Carlo. The uncertainty of Monte Carlo simulation for this section was 1.4 %. Thus, the statistical of the Monte Carlo was quite good. The GPR of the PDD and beam profile were 99.8 % and 99.2 % for criteria of 2 %/2mm, respectively. In addition, validation is carried out according to the IAEA TRS-430 procedure by comparing the confidence limits in several areas on the PDD and the beam profile. The results are shown in Table 1.

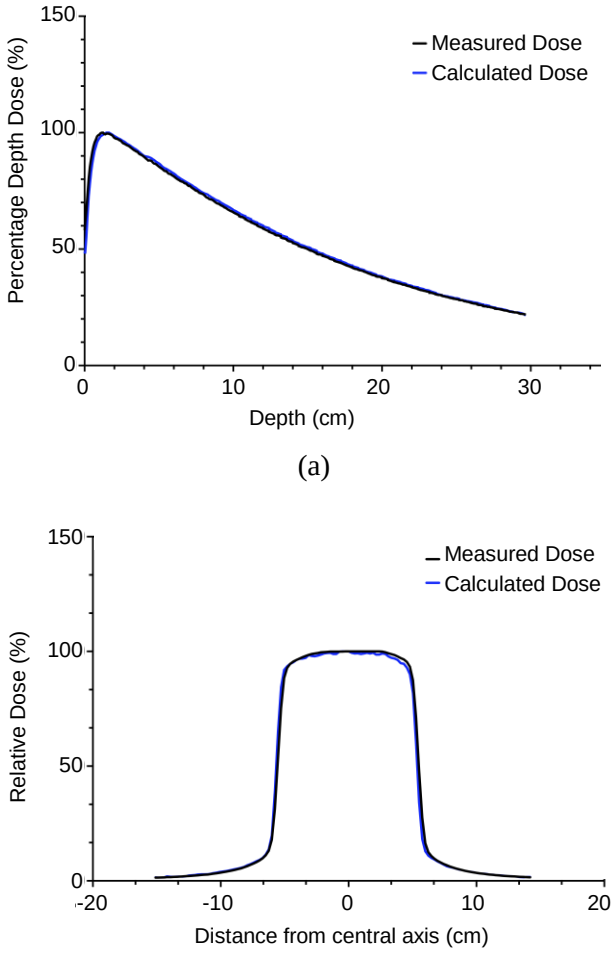

Fig. 2. (a) PDD and (b) beam profile of simulations in PRIMO (blue) and baseline data (black) at 10 × 10 cm^2 and 10 depths for the beam profile.

Table 1. Evaluation points on PDD and beam profile for a 10 × 10 cm^2 field at a depth of 10 cm.

Properties	Area	Evaluation	Tolerance Limit
PDD	δ_1	2.2 %	2 %
	δ_2	1.3 mm	2 mm
Beam Profile	δ_2	0.2 mm	2 mm
	δ_3	1.8 %	3 %
	δ_4	10.4 %	30 %
	δ_{50-90}	0.2 mm	2 mm
	RW_{50}	0.03 mm	2 mm

From the evaluation conducted, the simulation parameters for the 6 MV photon beam on PRIMO matched the radiation output of the 6 MV photon radiation of the Varian iX linac at our hospital. To obtain the absolute dose in the Monte Carlo simulation, a calibration value was needed between the Monte Carlo results and the baseline. This is because the simulation result unit is in eV/g while the desired dose has a unit of Gy. Based on the reference measurement on the linac, the measurement dose rate value is 0.943 cGy/MU at a depth of 10 cm with a field size of 10 × 10 cm^2. While the output value of the Monte Carlo simulation is 0.8 eV/g. Therefore, the calibration factor of the Monte Carlo simulation reference dose estimate is 1.2 cGy/MU g/eV.

Monte Carlo evaluation on RANDO phantom

To generate dose distributions, each patient's planning data was simulated individually. These patient-dependent segments require approximately 3 hours for each treatment. Dosimetry evaluation was conducted to determine the distribution of doses in the tissue exposed to radiation. For PTV, HI and CI were used as the evaluation metrics. On the other hand, dose constraints recommended by Radiation Therapy Oncology Group (RTOG) was employed for OAR evaluation.

The HI and CI of this study can be seen in Table 2. The HI value approaching zero indicates better dose coverage in the target volume, and the CI value approaching one indicates prescription dose coverage in the target volume by minimizing OAR exposure. In the TPS, the 3DCRT technique produces a relatively high HI value (0.2), which was possible that most of the dose was distributed in the periphery of the target due to parallel opposing technique. In the IMRT technique produced excellent HI values (0.1), indicating a more uniform dose distribution to the target. VMAT showed HI equal to IMRT. Furthermore, both RT-plans and dynalog files were imported to PRIMO Monte Carlo and showed that the HI for 3DCRT remains constant rather with deviation of 0.02 than IMRT and VMAT where the deviation were 0.1 and 0.3, respectively.

The CI value for the CI parameter in all techniques was generally high (≥ 0.95), except for the VMAT technique (0.68). The difference in CI values between 3DCRT and IMRT techniques for CI parameters was 0.02. This indicates that both techniques have almost the same level of accuracy when it comes to achieving the coverage

distribution on the target. Similar to HI, the smallest deviation of CI when compared to MC simulation was found on 3DCRT with a standard deviation of 0.01, while the IMRT and VMAT were 0.1 and 0.1. Additional dose statistics for PTV were deficit in Table 2.

Table 2. Comparison of dose evaluation parameters on PTV for three technique variations (3DCRT, IMRT, VMAT) and three calculation methods (TPS, MC,MC Log).

Or-gan	Para-meter Dosis	3D CRT			IMRT			VMAT		
		TPS	MC	MC Log	TPS	MC	MC Log	TPS	MC	MC Log
PTV	HI	0.2	0.2	0.2	0.1	0.4	0.2	0.1	0.2	0.8
	CI	1.0	0.9	0.9	1.0	0.8	1.0	1.0	0.9	0.7
	Dmean (Gy)	5130	50.7	50.7	55.5	51.6	51.8	59.5	50.8	54.4
	D2 (Gy)	5306.6	5348.1	5347.9	5333.6	6181.1	5521.2	5354.2	5418.6	7688.8
	D98 (Gy)	4495.0	4325.3	4325.9	4921.7	4159.6	4691.6	4619.5	4319.5	3255.0
	V90 (%)	97.9	96.5	96.6	99.9	91.9	99.0	96.1	96.6	74.5
	V95(%)	94.9	92.8	92.8	99.6	81.1	97.4	95.0	92.1	67.8

*MC = Monte Carlo simulation with input from RT-plan
MC Log = Monte Carlo simulation with dynalog input

Organ at risk evaluation

Table 3. Comparison of dose evaluation parameters on various OARs for three techniques variations (3DCRT, IMRT, VMAT) and three calculation methods (TPS, MC, MC Log).

OAR	Dose Parameters	3D CRT			IMRT			VMAT		
		TPS	MC	MC Log	TPS	MC	MC Log	TPS	MC	MC Log
Total Lungs	D_{mean} (Gy)	1.1	1.2	1.2	7.7	3.6	7.9	4.0	4.2	3.7
	V_5 (%)	3.3	3.3	3.3	57.3	17.2	58.4	22.5	23.4	18.4
	V_{10} (%)	1.8	2.1	2.1	27.8	16.9	28.9	9.1	9.9	8.2
Lung Ipsi	D_{mean} (Gy)	2.3	2.4	2.4	10.9	7.1	11.0	5.9	6.1	5.8
	V_5 (%)	7.2	7.2	7.2	64.8	32.3	65.1	32.4	32.4	30.8
	V_{10} (%)	3.9	4.6	4.6	52.6	32.2	52.5	19.1	20.1	17.9
	V_{20} (%)	2.4	3.0	3.0	15.1	16.5	15.9	7.1	7.9	7.3
	V_{30} (%)	1.7	2.3	2.3	3.2	4.7	4.2	2.3	3.1	2.9
Lung Contra	D_{mean} (Gy)	0.1	0.3	0.3	5.1	0.6	5.3	2.5	2.6	1.9
	V_5 (%)	0.0	0.0	0.0	50.9	4.4	52.7	14.3	15.9	7.9
	V_{10} (%)	0.0	0.0	0.0	7.2	4.1	8.9	0.7	1.36	0.0
Breast Cons	D_{mean} (Gy)	0.9	1.6	1.6	6.2	2.4	6.7	6.8	7.3	5.5
	D_1 (Gy)	18.5	27.6	27.6	19.8	24.2	23.9	20.3	22.3	17.5
Heart	D_{mean} (Gy)	1.3	1.2	1.2	14.4	12.0	14.4	6.9	6.9	7.4
	V_5 (%)	0.9	1.2	1.3	100.0	74.8	100.0	59.2	58.4	67.8
	V_{10} (%)	0.3	0.5	0.5	92.8	74.4	93.3	21.8	21.5	25.1
	V_{25} (%)	0.0	0.1	0.1	1.1	2.1	1.2	0.1	0.3	0.0
Spinal cord	D_1 (Gy)	0.3	0.3	0.3	9.2	10.7	9.0	2.2	2.3	2.4

Table 4. Global gamma pass rate of Monte Carlo and treatment plan.

Technique	GPR (%)	
	MC-TPS	MC Log-TPS
3DCRT	99.67	99.69
IMRT	99.98	99.50
VMAT	99.91	66.86

This study focuses on the analysis of the average dose, low and high dose distribution, and other critical parameters on vital organs such as the lungs, heart, and spinal cord. The evaluation results are summarized in detail in Table 3. The mean dose (D_{mean}) for the total lung showed significant variation between techniques and calculation methods. The IMRT technique with the MC Log method produced the highest D_{mean} of 7.9 Gy, while the 3DCRT technique with TPS recorded the lowest value of 1.1 Gy. For the Ipsilateral lung, the highest D_{mean} was 11.0 Gy found on the MC with dynalog input, which reflects a greater dose exposure on the target side. In contrast, the 3DCRT technique with TPS shows the lowest D_{mean} of 2.3 Gy, which indicates better protection for OARs on the ipsilateral side. The exposed dose to the contralateral lung was consistently lower than the ipsilateral. The IMRT technique with MC Log recorded the highest D_{mean} value of 5.2 Gy, while the 3DCRT technique gave a lower value, approaching zero. This suggested that IMRT, although more precise in targeting, can result in dose spread to the contralateral side. The heart was one of the critical organs that required special attention. The IMRT technique showed the highest D_{mean} of 14.4 Gy (MC Log), beyond VMAT (6.9 Gy) and 3DCRT (1.3 Gy, TPS). The low dose volume distribution (V_5) reached 100 % in IMRT. The VMAT technique provides better protection to the heart with a more limited dose distribution. The highest maximum dose (D_1) to the spinal cord was recorded by IMRT at 10.7 Gy (MC Log). In contrast, the 3DCRT technique with TPS showed the lowest D_1 at 0.3 Gy, indicating the ability of this technique to protect the spinal cord from high-dose exposure. In addition, we evaluate the gamma index between MC-TPS and MC Log-TPS. The global GPR with 3 %/3mm criteria and 10 % dose threshold is shown in Table 4.

DISCUSSION

This study uses Monte Carlo PRIMO based software that allows modeling of 6 MV photon beam linac. Simulations performed in the first PRIMO segment will produce PSF containing information on energy, direction, angle, and particles under the chamber monitor. This PSF is then used for simulations in the next segment. This file will be validated to match the output of the linac used at MRCCC Siloam Semanggi Hospital.

The area at each point on the PDD along *the central beam axis* after d_{max}having a deviation tolerance limit of 2 %. While the *build-up area* is a high dose gradient area, a shift in position can cause a significant change in dose, therefore, the tolerance limit is prioritized at 2 mm [17]. In each area $\delta_1$andδ_2 has a *confidence limit value* that is still within the tolerance limit. For a field size of 10 × 10 cm^2, the value δ_1 is 2.2 %, while the value $\delta_2$is 0.3 mm. This causes the average deviation value to be larger and the standard deviation to be high [13]. Therefore, the *confidence limit value* exceeds the specified limit.

This area is an area within the beam field size but outside *the central beam axis* which is a high dose area and a small dose gradient. CI and HI in Table 2 are obtained using Eq. (1) and (2). By looking at the comparison between the results of the planning reconstruction simulation, sometimes the HI value in IMRT has more satisfactory results than VMAT. This shows that the dose coverage in both techniques does not have a definite difference, and none is superior to the other [17,18]. Different results are obtained when we compare the results of the dynalog file reconstruction simulation, HI in VMAT shows more satisfactory results than HI in IMRT in all patients. The HI value from the planning reconstruction simulation with the dynalog file in IMRT has a significant difference. In Table 3 the results of the dynalog file reconstruction are always greater than the planning. This difference is not found in VMAT, the difference between the results of the planning reconstruction and the dynalog file does not have a significant difference. These results agreed with Qodarul et al (2025) that VMAT had more satisfactory results than the HI value of IMRT [19].

The low CI value of the VMAT technique for the CI parameter (0.7) may be due to the complexity of dose planning for this technique. VMAT allows for more conformal dose distribution but also increases the risk of uncertainty in planning. The low HI value of the IMRT technique shows the superiority of this technique in producing a more uniform dose distribution on tumor targets. This is very important to minimize damage to the healthy tissue around the tumor. The small difference in CI values between 3D CRT and IMRT suggests that IMRT does not necessarily provide a significant advantage in terms of dose accuracy for CI parameters. However, the main advantage of IMRT lies in its ability to produce more conformal dose distributions. Meanwhile, in Table 3, the low dose volume parameter (V_5) also showed a significant difference, with IMRT (58.4 %, MC Log) showing a wider dose distribution than 3DCRT (3.3 %, TPS). This difference indicates that IMRT has a wider dose spread, which may increase the risk of lung toxicity.

The dose volume distribution confirms that the VMAT technique excels in balancing target

coverage and OAR protection. In other words, VMAT provided more uniform dose coverage to the target while minimizing the dose to the OARs, particularly to the ipsilateral and contralateral lungs.

However, the IMRT technique shows some weaknesses, especially in parameters such as D_{mean} and V_5 for heart and lung. This indicates a potential increase in the risk of toxicity that requires close monitoring. Meanwhile, 3DCRT has advantages in OAR protection but has shortcomings in target coverage, especially in dose homogeneity and conformity.

Almost all of the studies reported a GPR (Gamma Passing Rate) higher than 95 %. However, for the VMAT log, the GPR dropped significantly to 66.86 %. This indicates a substantial difference in dose distribution between Monte Carlo (MC) calculations using dynalog input and the Treatment Planning System (TPS). This result is consistent with the dosimetry values shown in Tables 2 and 4, where VMAT demonstrated the lowest quality in terms of Homogeneity Index (HI) and Conformity Index (CI). Azzi et al. (2023) and Qodarul et al. (2025) suggested that dose verification based on linac log files should take into account the data stream frequency and the limitations of the software's internal processing [11,19].

CONCLUSION

This study found the 3DCRT showing superior HI, CI, and OAR sparing compared to IMRT and VMAT when the Linac log file was implemented. However, since real patient anatomy varies, technique selection should be personalized, balancing these parameters. IMRT and VMAT displayed discrepancies between TPS and Monte Carlo-simulated Linac log data, suggesting issues in data transfer that require further investigation.

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AUTHOR CONTRIBUTION

Rendra Dandi Sugandi and Akbar Azzi equally contributed to this paper as the main authors. Muhammad Fadli contributed to data collection. Dwi Seno Kuncoro Sihono agreed and approved the final version of the paper.

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