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Gamma passing rate evaluation for IMRT and VMAT techniques based on gantry angles

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Abstract: Introduction: The accuracy of radiation dose delivery in advanced techniques such as Intensity Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) is highly dependent on the consistency of gantry angle performance. This study aims to evaluate the effect of gantry angle variations on the gamma passing rate (GPR) in IMRT and VMAT treatment plans. Methods: IMRT and VMAT plans were created using the Monaco Treatment Planning System on a homogeneous slab phantom and delivered within a range of gantry angles, including 90°, 180°, 270°, and 360°. Measurements were performed using the 2D array PTW Octavius 1500 that delivered by Linac Elekta Synergy and analyzed with the Verisoft software, applying a 2%/2 mm gamma index with a 10% threshold and a 97% gamma passing rate criterion. Results: All plans achieved GPR above 97%. VMAT demonstrated higher GPR values than IMRT at gantry angles of 90°, 180°, 270°, with the largest difference of 0.8% observed at 270°. IMRT showed a slightly higher GRP value than VMAT at range gantry 360° with a difference of 0.1%. Conclusion: The higher GPR value observed in VMAT indicates greater stability in relation to gantry angle variations. Although, IMRT performed slightly better at 360°, the difference was minimal. In general, gantry angle dependence was observed in both techniques, but the variation was not clinically significant.

Keyword : IMRT, VMAT, GPR, Gantry Angle

1. Introduction

Cancer remains one of the leading causes of mortality in Indonesia, with 408,661 new cancer cases and 242,988 deaths reported in 2022 (Ferlay et al., 2024). Radiotherapy is a primary treatment modality needed for over 50% of cancer patients (Octavianus & Godhowiardjo, 2022). However, access to advanced radiotherapy techniques remains limited in some regions, necessitating continuous advancements in treatment methodologies to improve patient outcomes (Borne & Nobile, 2024).

Among modern radiotherapy techniques, Volumetric Modulated Arc Therapy (VMAT) and Intensity-Modulated Radiation Therapy (IMRT) have revolutionized cancer treatment by providing highly conformal dose distributions and minimizing exposure to surrounding healthy tissues(Chan et al., 2021). These techniques allow for better dose modulation, shorter treatment times, and enhanced therapeutic efficacy (Zhou et al., 2024). With the growing adoption of VMAT and IMRT in Indonesia, ensuring their accuracy and safety has become a critical concern(Teng et al., 2024).

Patient-Specific Quality Assurance (PSQA) is essential in maintaining high treatment standards in radiotherapy (Chan et al., 2021). PSQA involves verifying the accuracy of planned dose distributions before actual patient treatment, ensuring that deviations from the prescribed radiation dose remain within acceptable limits(Zhou et al., 2024). One of the key components of PSQA is the use of two-dimensional (2D) detector arrays to measure and validate dose delivery, addressing potential discrepancies in complex radiation delivery techniques such as VMAT and IMRT(Teng et al., 2024). Radiotherapy with VMAT and IMRT techniques is currently widely used due to its ability to deliver more precise and efficient doses to the target. However, there are challenges in dose verification, especially in the effect of gantry angle variations on detector response. Han et al. reported that gantry angle variations can cause up to 8% response differences in detector systems such as, indicating the importance of gantry angle evaluation in dose plan QA (Han et al., 2010).

Recent studies have explored the angular response characteristics of 2D detector arrays used in PSQA for VMAT and IMRT (Chan et al., 2021). However, there is no standard approach found for stopping or reducing frequency of measurements. On the other hand, the angular dependence of these detectors can influence the accuracy of dose verification, leading to potential uncertainties in treatment quality control(Zhou et al., 2024). Studies such as Chan et al. (2021) and Zhou et al. (2024) have highlighted the need for calibration and correction methods to account for angular response variations, ultimately improving the reliability of PSQA measurements(Chan et al., 2021; Zhou et al., 2024). Additionally, Teng et al. (2024) have demonstrated the potential of high-resolution CMOS 2D detector arrays in ensuring PSQA accuracy (Teng et al., 2024). Furthermore, Dogan et al. (2023) have investigated the use of electronic portal imaging devices (EPIDs) for pre-treatment and in vivo dosimetry in PSQA, offering another approach to dose verification(Dogan et al., 2023). However, there has been no study on the effect of differences in gantry angle responses on LINACs and detectors for IMRT and VMAT techniques.

This study aims to further investigate the differences in angular responses on the Octavius type 1500 PTW 2D array detector in PSQA for VMAT and IMRT and analyze its impact on dose verification accuracy. This will contribute to improving quality assurance protocols, ensuring safer and more effective radiotherapy treatments.

2. Materials and Methods

This study employed the Monaco Treatment Planning System (TPS) version 6.1.2.0 (Elekta Solutions AB, Stockholm, Sweden). The latest iteration of this system integrates both physical and biological modelling in the optimization of radiotherapy dose

distribution. Monaco facilitates biologically guided optimization through the implementation of three biological constraints—Equivalent Uniform Dose (EUD) for target structures, as well as Serial and Parallel models for organs-at-risk (OARs). In parallel, six physical constraints are available, including Target Penalty, Quadratic Overdose, Overdose Dose–Volume Histogram (DVH), Underdose DVH, Maximum Dose, and Quadratic Underdose (Pyshniak et al., 2014).

One of Monaco's distinguishing features is its robust cost function-based optimization algorithm, which enables precise modulation of dose distribution to satisfy both PTV coverage and OAR sparing objectives. The system permits customization of tissue-specific radiosensitivity via EUD parameters and supports the classification of OARs as serial or parallel based on their radiobiological architecture (Pyshniak et al., 2014; Radhakrishnan et al., 2017). These functionalities afford a high degree of flexibility in treatment planning, enabling a nuanced balance between maximizing tumours dose conformity and minimizing exposure to adjacent normal tissues. Furthermore, the simultaneous application of biological and physical constraints facilitates the generation of homogeneous and clinically optimal treatment plans by minimizing both underdosage and overdosage in critical structures and target volumes (Sukhikh et al., 2017).

Monaco employs a two-stage optimization strategy to generate clinically deliverable treatment plans with high dosimetry accuracy. In the first stage, the system aims to establish an ideal fluence map for each beam, beginning with the definition of dose voxels, projection of the planning target volume (PTV), and preliminary dose calculation using the enhanced pencil beam algorithm. Fluence optimization is performed using an unconstrained approach based on the conjugate gradient algorithm, which iteratively minimizes the objective function and is subsequently refined to satisfy all specified physical and biological constraints (Senthilkumar & Maria Das, 2019). The second stage addresses the deliverability of the optimized fluence by the linear accelerator (LINAC). This involves converting the idealized fluence maps into a sequence of machine-executable segments and determining the dynamic trajectory of the multi-leaf collimator (MLC) based on dose rate modulation. At this stage, dose calculation is performed using a voxel-based Monte Carlo algorithm, which provides superior accuracy in heterogeneous media, particularly in the presence of tissue density variations (Clements et al., 2018).

2.1. Imaging and Contouring

CT simulation was conducted using a homogeneous slab phantom with a thickness of 20 cm to approximate human anatomical geometry (Fig. 1). Image acquisition was performed using a GE Discovery RT 64-slice CT simulator, with parameters set to a slice thickness of 2.5 mm and a field of view (FOV) of 40 cm (Fig. 2). The acquired DICOM-formatted images were subsequently imported into the Monaco Treatment Planning System for further processing. Within the planning system, simple target volumes and representative normal tissue structures were delineated. A cylindrical planning target volume (PTV) was defined at the geometric center of the slab phantom to serve as the irradiation target.

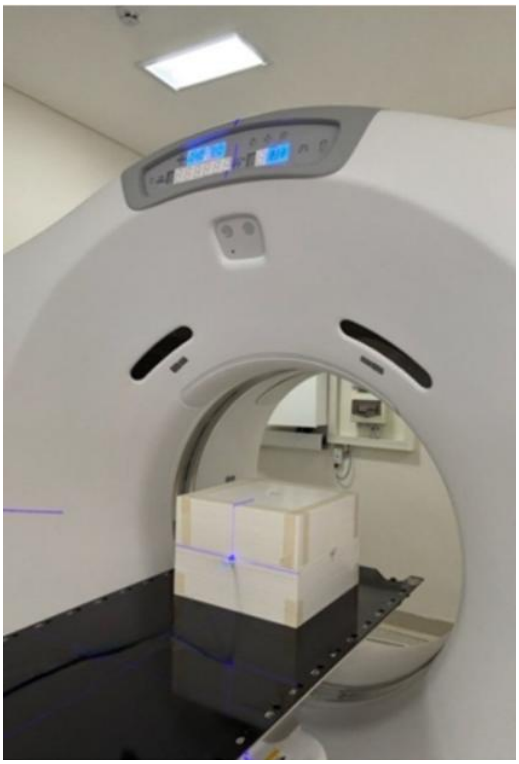

Figure 1. Setting for imaging and contouring used slab phantom

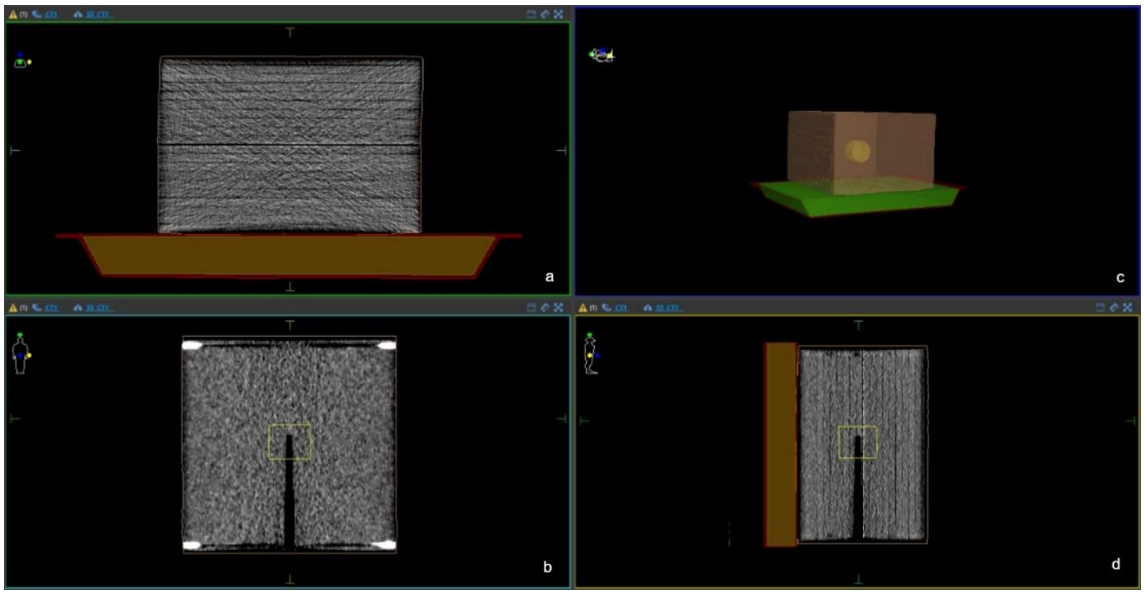

Figure 2. Contouring with view a. Transversal b. Coronal c. Beam Eye View and d. Sagittal

2.2. Planning Parameter Used in TPS

The treatment planning system utilized in this study was Monaco version 6.1.2.0 (Elekta Solutions AB, Stockholm, Sweden). Two advanced radiotherapy techniques were employed: Intensity-Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT). The configuration parameters for the treatment planning system are summarized in Table 1.

All IMRT and VMAT plans were generated using a dose calculation grid spacing of 3 mm and a Monte Carlo variance of 1%. For VMAT planning, the following sequencing parameters were applied: a maximum of one arc per plan, up to 150 control points per arc, a minimum segment width of 0.5 cm, and a medium fluence smoothing level. For IMRT plans, a maximum of 30 control points per beam was allowed, with a minimum segment width of 0.5 cm and a fluence smoothing level also set to medium.

Each plan—both IMRT and VMAT—underwent a single Stage 1 optimization followed by a single Stage 2 optimization. Detailed beam configuration settings for IMRT and VMAT plans are presented in Tables 2 and 3, respectively.

Table 1. The previsions for treatment planning system setup

No	Parameters	Value
1.	Energy	6 MV
2.	Prescription Dose	25 x 2 Gy
3.	PTV achievement	V95% > 95% V107% < 2%
4.	Planning Isocenter	X=Y=Z=0 (According to the origin point specified during CT Sim)
5.	Technic	IMRT dan VMAT

Table 2. Gantry angle variation for IMRT

No	Angle Range	Gantry Angle
1	90	315˚, 345˚, 15˚, 45˚,
2	180	315˚, 345˚, 15˚, 45˚, 75˚, 105˚, 135˚
3	270	315˚, 345˚, 15˚, 45˚, 75˚, 105˚, 135˚, 165˚, 195, 225˚
4	360	315˚, 345˚, 15˚, 45˚, 75˚, 105˚, 135˚, 165˚, 195, 225˚, 255˚, 285˚

Table 3. Gantry angle variations for VMAT

No	Planning	Angle range	Total beam	Direction beam	Gantry start (°)	Arc	Increment
1	VMAT90	90	1	CW	315°	90	30
2	VMAT180	180	1		315˚	180	
3	VMAT270	270	3		315˚ 135˚ 180˚	180 45 45	
4	VMAT360	360	3		315˚ 135˚ 180˚	180 45 135	

2.3. Planning QA Process: PTW Octavius Phantom

After planning was completed, it continued with QA plan. QA planning was made to obtain the results of dose calculation on the Oktavius phantom at TPS. The type of detector used for the implementation of QA Plan TPS was 2D array PTW Octavius detector 1500 type, ionization chamber detector type. The QA plan process began with creating a QA plan on the TPS Monaco system, where radiation parameters from patient planning such as monitor units (MU), gantry angles, and MLC leaf configurations were copied and adjusted to the Octavius phantom geometry (Fig.3).

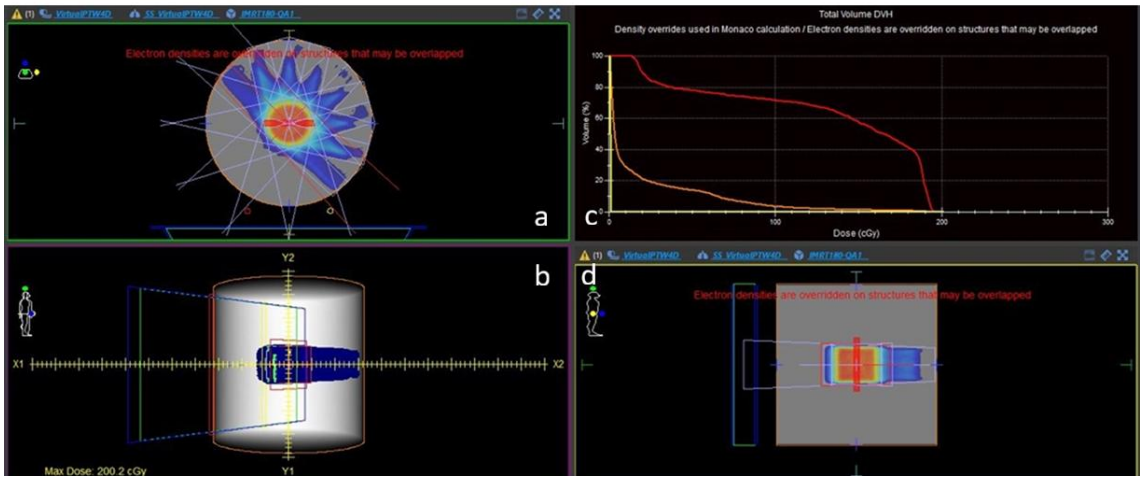

Figure 3 QA Planning at virtual Octavius Phantom a. Transversal b. BEV c. DVH d. Sagittal

The QA planning was run on LINAC that delivered by Mosaiq version 2.83 (Electa. Inc., California, USA). Then, the QA planning file was exported in DICOM format and imported into the QA analysis software, in this study the software used was Verisoft version 8.1 (8.1.1.0). Furthermore, the Octavius phantom was prepared by placing the detector module at the isocenter position and positioned precisely on the linac table using a laser system (Fig.4). The QA plan was then run on the linac, and during the irradiation process, the detector on the phantom recorded the actual dose distribution. The irradiation data were analyzed using Verisoft software, which compared the measured dose distribution with the dose distribution calculated from the TPS through 3D gamma index analysis with evaluation criteria including DD 2%, DTA 2mm, normalization method of analysis with local gamma, threshold 10% and passing rate ≥ 97%.

Figure 4 Setting for QA planning using Octavius phantom

3. Results and Discussions

Both IMRT and VMAT, gantry angle was tested at several ranges of motion (90°, 180°, 270°, and 360°) using two verification systems: Mosaiq (Radiation Recording System) and Verisoft (Independent Verification System). The accuracy and consistency of gantry angle recording between the Mosaiq system and Verisoft software were evaluated during patient-specific quality assurance (PSQA) measurements using the Octavius phantom. Two treatment techniques—IMRT and VMAT—were assessed across four gantry angle ranges: 90°, 180°, 270°, and 360°. The gantry angles recorded by both systems at various measurement points were compared, and the observed differences are presented in Table 4.

The standard deviation (SD) of the recorded gantry angle for the IMRT technique ranged from 0.0° to 0.5°. Meanwhile, for VMAT, the SD was slightly lower, ranging from 0.1° to 0.2°. These findings demonstrate that VMAT exhibits better angular stability than IMRT. The larger deviations in IMRT were primarily observed at certain gantry positions, especially at 270° and 360°, which may be attributed to the step-and-shoot delivery technique that introduces abrupt segment transitions. In contrast, VMAT employs continuous gantry rotation, allowing smoother transitions and greater mechanical consistency. This observation is consistent with the findings of Fuangrod et al., who emphasized the need for QA systems to accommodate angular variations and incorporate real-time verification to ensure clinical accuracy (Zwan et al., 2016).

Table 4. The difference of gantry angle using Mosaiq and Verisoft

	Gantry Angle	Range 90			Range 180			Range 270			Range 360		
		Mosaiq	Verisoft	SD	Mosaiq	Verisoft	SD	Mosaiq	Verisoft	SD	Mosaiq	Verisoft	SD
IMRT	315	315	314.9	0.1	315	314.9	0.1	315	314.9	0.1	314.9	314.8	0.1
	345	345	344.9	0.1	345	345.1	0.1	345	345.1	0.1	345	345.1	0.1
	15	15	15.2	0.1	15	15.2	0.1	15	15.2	0.1	15	15.2	0.1
	45	45	45.2	0.1	45	45.2	0.1	45	45.2	0.1	45	45.2	0.1
	75				75	75	0.0	75	75	0.0	75	75.1	0.1
	105				105	104.8	0.1	105	104.8	0.1	105	104.9	0.1
	135				134.9	134.7	0.1	134.9	134.7	0.1	135	134.7	0.2

	165							164.9	164.3	0.4	165	164.4	0.4
	195							195	194.5	0.4	195	194.5	0.4
	225							224.9	224.3	0.4	224.8	224.1	0.5
	255										254.9	254.4	0.4
	285										284.9	284.6	0.2
VMAT	arc 1	314.9	314.8	0.1	314.9	314.8	0.1	135	134.7	0.2	134.9	134.6	0.2
	arc 2							180	179.8	0.1	180	179.5	0.4
	arc 3							315	314.9	0.1	315	314.9	0.1

QA planning in IMRT and VMAT not only ensures the conformity between the therapy plan and actual clinical delivery but also plays a vital role in maintaining patient safety and the accuracy of dose delivery. Mechanical parameters such as gantry angle, collimator motion, and multi-leaf collimator (MLC) speed significantly influence the reliability of QA processes(Miften et al., 2018). In terms of dosimetry verification, the gamma passing rate (GPR) serves as a quantitative indicator of agreement between calculated and measured dose distributions(Khan & Gibbons, 2014). According to the American Association of Physicists in Medicine (AAPM) Task Group 218 (TG-218), a GPR of at least 95% using the 3%/2 mm criterion is recommended as the clinical acceptance threshold for IMRT and VMAT QA(Miften et al., 2018). In this study, both techniques generally achieved GPRs exceeding the tolerance limit. However, a downward trend in GPR was observed with increasing gantry angle deviation, particularly in cases involving IMRT at 270° and 360°, as well as VMAT at 270° and 360°.

Overall, the VMAT technique demonstrated a more stable and consistent gamma index performance compared to IMRT across most of the evaluated gantry angle variations, specifically at 90°, 180°, and 270°. As shown in Table 5 and Figure 5, the gamma passing rate for VMAT was higher than that of IMRT at all three angles, with the largest difference of 0.8% observed at 270°. This indicates that VMAT possesses greater robustness against angular variations in dose delivery.

Nevertheless, a mild angular dependence was observed, particularly at extreme angles such as 270° and 360°, where a slight decline in gamma passing rate was evident, especially for the IMRT technique. Interestingly, at a gantry angle of 360°, IMRT achieved a gamma passing rate of 97.2%, which was marginally higher (by 0.1%) than that of VMAT.

These findings suggest that while VMAT generally demonstrates superior consistency in dose verification, IMRT may yield higher accuracy at specific gantry angles, depending on the dose distribution characteristics and the configuration of the treatment planning system employed.

Table 5. Gamma passing rate comparison of IMRT and VMAT

Gantry angle	IMRT (%)*	VMAT (%)*	SD
90	99.7	100.0	0.3
180	99.4	99.8	0.4
270	98.1	98.9	0.8
360	97.2	97.1	0.1

**Gamma Passing Criteria: 97.0% to 100.0% based on local limit.*

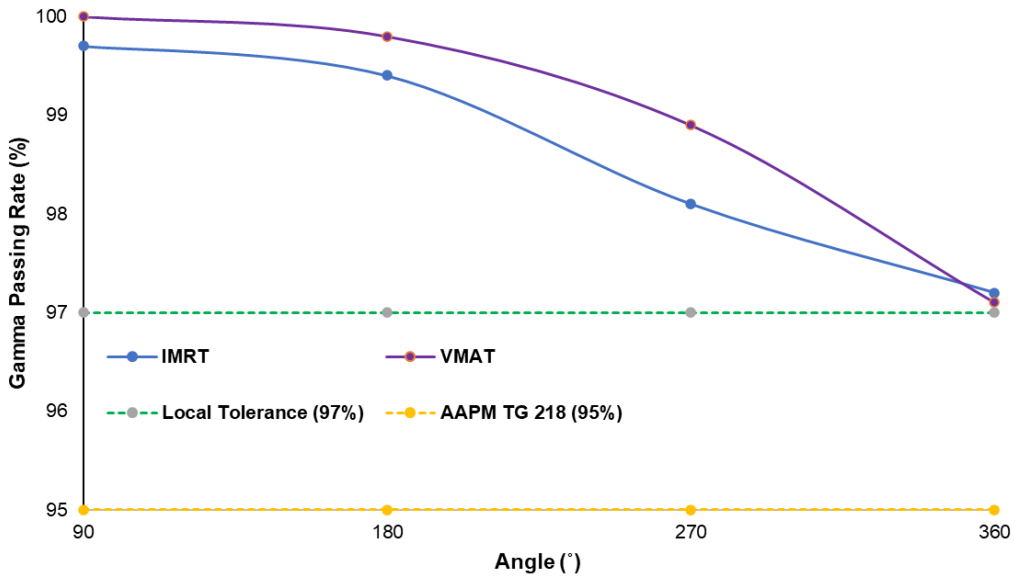

Figure 5 Graph of IMRT and VMAT Gamma passing rate

These findings are in line with previous studies. Kumar et al. reported that the 2D *seven29* ion chamber array used in IMRT QA exhibits angular dependence, which can reduce verification accuracy when the detector is exposed to oblique beam angles(Kumar et al., 2015). Similarly, Gorobets et al. noted that the PTW Octavius 1500 detector has a standard angular deviation of approximately 0.3, with the largest deviations occurring when the beam passes near the couch edge, where dosimetric uncertainties are inherently higher(Gorobets et al., 2024). This corresponds with the results in this study, where the standard deviation exceeded 0.3 at IMRT 270°, IMRT 360°, and VMAT 360°.

Overall, the consistency between gantry angles recorded by Mosaiq and Verisoft confirms their reliability in QA workflows. Although all deviations remained within acceptable clinical thresholds, their influence on the gamma passing rate underscores the need for careful consideration of gantry angle accuracy, especially at extreme angles. Integrating QA procedures that account for mechanical variabilities, angular sensitivity, and real-time verification is essential for maintaining high standards of treatment quality and patient safety in both IMRT and VMAT techniques.

4. Conclusions

The results of this study indicate that the VMAT technique offers greater angular stability than IMRT, as evidenced by consistently higher gamma passing rates across various gantry angles. Although IMRT slightly outperformed VMAT at the 360° angle, the difference was clinically insignificant. Overall, both techniques exhibited mild angular dependence.

Therefore, additional QA attention is recommended when using IMRT at extreme gantry angles (270° and 360°) to ensure accurate dose delivery. These findings support the incorporation of gantry-angle-aware QA protocols, especially in clinics utilizing the Octavius 1500 2D array system.

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