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ASSESSMENT OF PHOTON BEAM PARAMETERS OF THE VARIAN CLINAC IX LINEAR ACCELERATOR

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ABSTRACT

Radiation therapy accuracy and consistency are crucial in cancer treatment. However, technical issues such as machine breakdowns, can compromise radiation delivery, leading to non-uniform dose distribution, hot or cold spots, and, suboptimal treatment outcomes including local tumor recurrence. This study assesses the photon beam parameters of the Varian Clinac iX Linear Accelerator at Komfo Anokye Teaching Hospital to ensure the machine's clinical reliability. Beam profiles were analyzed for 6 MV and 16 MV photon energies, using a 30 x 30 x 30 cm^3 water phantom, electrometer, and ionization chamber. Measurements were taken at different depths for 10 × 10 cm^2 and 15 × 15 cm^2 field sizes. The beam flatness and symmetry of the 6 MV photon energy ranged from 0.88 % to 2.22 % and 0.25 % to 0.78 %, respectively, for the 10 × 10 cm^2 field size, and from 1.39 % to 2.34 % and 0.57 % to 0.96 %, respectively, for the 15 × 15 cm^2 field size. Flatness and symmetry for the 16 MV photon energy ranged from 1.98 % to 2.42 % and 0.36 % to 1.04 % for the 10 × 10 cm^2 field size, and from 1.25 % to 2.55 % and 0.25 % to 0.67 % for the 15 × 15 cm^2 field size. The measured charge for 6 MV photon was 16.59 nC while the 16 MV photon energy measured 19.28 nC. The findings indicate that the Linear Accelerator is in good condition for clinical use. However, regular quality control checks are recommended to maintain its performance and ensure the consistent and accurate cancer treatment.

Keywords: Radiation therapy, beam profile, quality control, phantom, target volume

INTRODUCTION

Ionizing radiation is a highly effective method for treating various types of cancer, primarily through the use of linear accelerators (LINACs). These devices generate high-energy x-rays and electrons, which are crucial for delivering external beam radiation therapy. The main objective of this treatment is to eradicate malignant cells while minimizing damage to surrounding healthy tissue (Platoni *et al*., 2018; Hanna, 2012). A LINAC, is a device that uses high-frequency electromagnetic waves to accelerate charged particles, such as electrons, to high energies through a linear conduit. To treat deep-seated cancers or superficial tumors, the high-energy beam can be utilized (Khan & Gibbons, 2014; Palmer, Kearton & Hayman, 2012; Beyzadeoglu, Ozyigit & Ebruli, 2010). The design of the flattening system and how the beams are fitted together determine the beam profiles. As the distance increases, the beams' flatness will drastically alter because scattered electrons have less energy (Pathak, Mishra, Singh & Mishra, 2015). Quality Assurance (QA) encompasses a series of systematic and planned activities implemented within a quality program. QA in radiotherapy encompasses a comprehensive set of processes aimed at ensuring that treatments consistently meet established quality standards. This involves systematic verification and validation of all components involved in delivering radiation therapy, ensuring adherence to the prescribed treatment protocols. The QA framework is essential for minimizing errors and enhancing patient safety throughout the treatment process (Vetter & Stoeva, 2016; Van Dyk, 2015; Klein *et al*., 2009).

The study focused on assessing the QA of a LINAC and the primary objective was to ensure the operational reliability and safety of the LINAC, which is crucial for effective cancer treatment. The research utilised a STARTRAK device and Perspex materials to conduct QA tests over a period. The study involved measuring the output dose of the LINAC to evaluate its performance against established safety standards. Findings indicated that the output X-ray dose variations were within acceptable limits, specifically ±2 %, aligning with the manufacturer's specifications for the LINAC model used (Elekta). This suggests that the LINAC operated effectively within its designated parameters, ensuring safe and accurate radiation therapy for patients. The study successfully verified the QA processes for the LINAC at the Baghdad Center, demonstrating that it meets the necessary standards for delivering radiation therapy. This reinforces the importance of regular quality checks in maintaining high treatment standards in oncology settings (Lazim, Rejah & Alabedi, 2020; Rejah, 2019; Skinner *et al*. 2019).

Additionally, Patatoukas *et al.,* 2018 demonstrated various beam parameters, including penumbra, symmetry, and flatness, using multiple systems. They computed the dosage profile through a phantom and six ion chambers at different depths and field sizes, confirming that all measurements remained within the allowed range for assessing beam quality (Patatoukas *et al*., 2018). Radiation treatment aims to deliver the highest dose possible to the tumor site (target) while safeguarding the nearby healthy tissue (Thariat *et al*., 2013). High precision is needed throughout the entire process to accomplish this. The graphical depiction of the relative dose versus the distance from the central axis at a certain depth is called a beam profile (Adom, Addison, Awuah, Hasford & Owusu-Mensah, 2023). penumbra zone is a critical aspect of any radiation beam, whether from photons or electrons. It is defined as the region within the beam profile where the relative dose transitions from 80 % to 20 %. This zone is essential for accurate dosimetry, particularly in the context of linear accelerators (LINACs). A precise understanding of the penumbra breadth is a necessity for appropriate treatment planning. For instance, irradiating healthy tissues and creating needless huge fields can result from overestimating the penumbra width (Yuen, Hardcastle & Metcalfe, 2011).

Critical beam parameters recorded during the commissioning phase of a medical LINAC include photon output constancy and beam profile. These data serve as a reference for the subsequent QA program, which aims to ensure the accuracy and integrity of radiation dose distribution. By establishing and regularly monitoring these baseline parameters, any deviations from expected performance can be quickly identified and addressed, thus maintaining the safety and efficacy of the LINAC in external beam radiation treatment (Krauss *et al*., 2023; Aird, Mayles, & Mubata, 2021). The objective of this research was to evaluate the photon beam characteristics of the Varian Clinac iX Linear Accelerator, as depicted in Figure 2, at Komfo Anokye Teaching Hospital. This assessment focused on quantifying various beam parameters to ensure optimal performance and accuracy in clinical applications.

Factors Influencing Absorbed Dose Variation in Radiation Therapy

The absorbed dose in patients undergoing radiation therapy varies significantly with depth due to several interacting factors. These factors are crucial for optimizing treatment plans and ensuring effective dose delivery. Key factors influencing absorbed dose variation include:

Photon Beam Energy

Higher energy photon beams penetrate deeper into tissue, affecting the depth of maximum dose (Dmax). For instance:

- 6 MV beams have a Dmax of approximately 1.5 cm.
- 10 MV beams exhibit a Dmax of about 2.5 cm.

As energy increases, the Dmax also increases, allowing for more effective treatment of deeper tumors while reducing surface doses due to skin sparing effects (Buzurovic, Mott, Perez-Catalayud & Zuchora, 2023; Khaledi *et al*., 2022).

The engrossed dosage in the patient fluctuates with depth as the beam unintentionally strikes the patient or the phantom. The photon beam's energy, depth, treatment field size, distance from the source to the patient's superficial, and beam collimation system are a few variables that affect the variation's change (Kry *et al*., 2017). The dose profile describes the radiation dose data collected by scanning a phantom upright to the beam axis. This profile is based on deepness of measurement and can be obtained in a variety of orientations, including diagonally, cross-plane, or along a straight line (Das *et al*., 2013). At a typical treatment depth (10 cm), dose profiles as shown in Figure 1 are taken to assess symmetry and flatness.

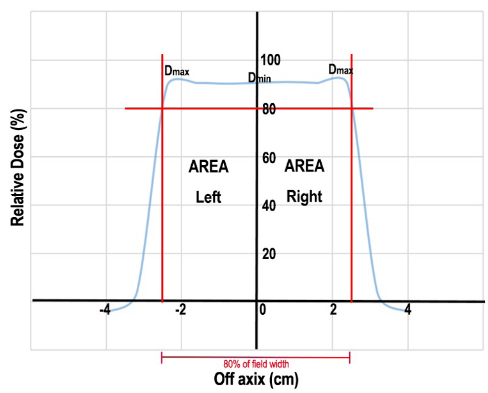


Figure 1: Photon Beam Profile (Winiecki *et al.*, 2022)

Beam flatness

Beam flatness (F), as indicated in Equation 1, measures the uniformity of the radiation emission across the treatment field. It is calculated by comparing the maximum and minimum doses in the profile (Goodall, Harding, Simpson, Alexander & Morgan, 2015). The degree of flatness is determined by measuring the inner 80 % of the beam (Lindborg, Hultqvist, Tedgren & Nikjoo, 2013). The standard specification for LINACs requires a flatness of 3 % when measured in a water phantom at a depth of 10 cm with a source to surface distance (SSD) of 100 cm (Cruz, Narayanasamy, Papanikolaou & Stathakis, 2015). AAPM Task Group 142 (TG-142) defines tolerance relative to baseline values to ensure alignment with the treatment planning system [8]. The National Council on Radiation Protection and Measurements (NCRP) report 69, recommends an absolute tolerance of ±3 % (Goodall, Harding, Simpson, Alexander & Morgan, 2015; Hanley, 2021).

$$F = \frac{D_{max} - D_{min}}{D_{max} + D_{min}} \times 100\ \% \qquad (1)$$

Beam symmetry

Beam symmetry (S), measures the uniformity of the beam dose throughout the beam profile. To guarantee beam symmetry, the lateral dose distributions on either side of the central axis must be compared. The American Association of Physicists in Medicine (AAPM) states that for any symmetrically situated pair of sites on opposing sides of the principal axis, the variation of the cross-beam profile in the reference plane should not exceed ±2 % (Hanley, 2021). The beam symmetry is determined by Equation 2.

$$\frac{Area_{left} - Area_{right}}{Area_{left} + Area_{right}} \times 100\ \% \qquad (2)$$

where S is the symmetry of the beam profile, $Area_{left}$ is the area of the beam profile left to the central axis and $Area_{right}$ is the area of the beam profile right to the central axis.

These equations are critical for ensuring that radiation doses delivered in radiotherapy are uniform and effective. They are used in clinical practice to guarantee that patients receive the best possible treatment while minimizing the risk to surrounding healthy tissues.

Photon Beam Output

Photon beam output in radiotherapy refers to the quantity of radiation energy delivered by a medical LINAC in the form of photon beams (Funk, Stockham & Laack, 2016). These photon beams are a fundamental component of external beam radiotherapy, a common approach for treating cancer and other medical conditions. The photon beam output is a crucial parameter as it directly determines patients' radiation dose during their treatment sessions. It is typically measured in monitor units (MU) per minute. To guarantee that the recommended radiation dose reaches the target area exactly while minimizing exposure to nearby healthy tissues, photon beam output accuracy and consistency are crucial. Photon beam output is one of the key factors that contribute to the overall quality and success of radiotherapy treatments. In order to minimize potential adverse effects for the patient and get the intended therapeutic objectives, it is imperative to maintain precise and consistent photon beam output (Goodman, 2013).

MATERIALS AND METHOD

Study Design

The research work had the consent of the Medical Physics group in the Oncology Directorate, Komfo Anokye Teaching Hospital (KATH), to carry out a phantom study on the dosimetric effect of radiation from the LINAC. This prospective study was conducted at the KATH's Oncology Directorate, Kumasi, Ghana from January 2023 to August 2023.

Table 1 provides detailed information about the technical specifications of the LINAC machine used in the study.

Table 1: Description of the Varian Clinac iX Linear Accelerator at KATH

Model	Year Installed	Photon Energies	Electron Energies	Treatment Delivery	Treatment couch
Varian Clinac iX	2019	6 MV and 16 MV	6, 9, 12 and 16 MeV	3D CRT, IMRT, IGRT, VMAT, SRS	Hexapod

Beam Profile for the Beam Energies

The assessment of photon beam profiles for two photon energies, 6 MV and 16 MV, was conducted on the Varian Clinac iX LINAC (Manufactured by Varian Medical System, USA) at the Oncology Directorate of KATH. The evaluation involved cross-plane profiles obtained from photon scan data measurements. The study employed a 30 x 30 x 30 cm^3 manual water phantom, an Exradin® A19 ionization chamber (SN: XAQ182113), and a Max 4000 Electrometer (SN: J182273). All setup measurements were carried out at a Source-to-Surface Distance (SSD) of 100 cm. Initially, a 10 x 10 cm^2 field size was used to deliver a 6 MV photon energy to a water phantom at a depth of 0 cm. Subsequent measurements were taken at depths of 5 cm, 10 cm, 15 cm, and 20 cm. To ensure consistent results, a warm-up procedure was performed and ionization chamber's effective point of measurement was aligned with the photon source. The field size then was changed to 15 x 15 cm^2 and normalized to the maximum dose depth (dmax) at the same SSD. The procedure was repeated for the 16 MV photon energy. Measurements were performed in a 30 x 30 x 30 cm^3 manual water medium, following the TG-142 protocol. Symmetry and flatness assessments for 6 MV and 16 MV cross-plane photon beams were conducted using Microsoft Excel spreadsheet for data analysis. The results obtained were compared against baseline values from acceptance and commissioning of the LINAC. Figure 2 shows the Manual Water Phantom set-up with the Varian Clinac iX LINAC for dosimetry.

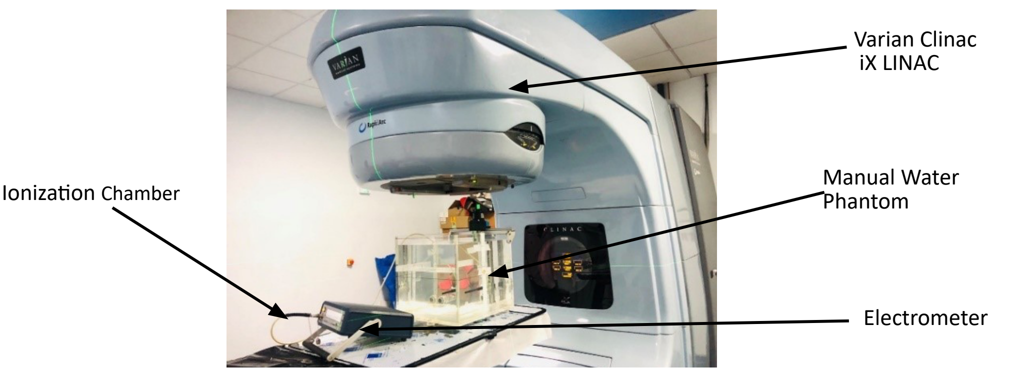


Figure 2: Experimental set-up with the manual water phantom

Photon Beam Output

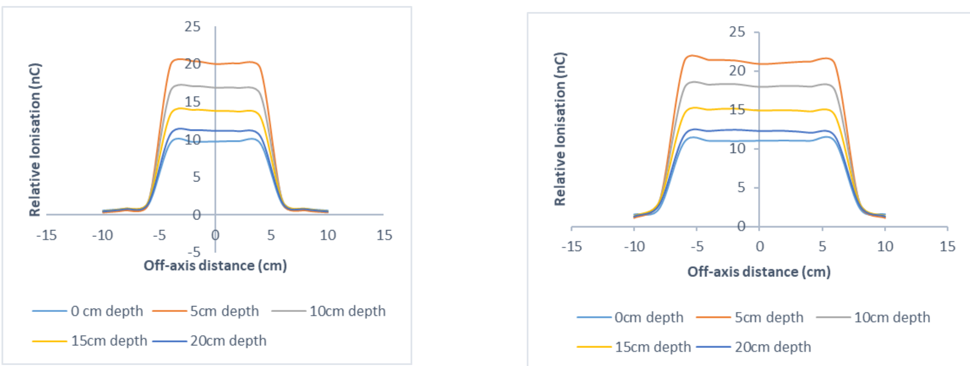
A solid phantom, ionization chamber, and electrometer were used to determine the photon beam output. The electrometer was warmed up and biased to +300 V, as per the AAPM Task Group 198 protocol [23], to ensure accurate and consistent measurements. Using a fixed dose rate of 400 MU/min, five (5) consistent electrometer readings were taken for the 6 MV photon beam energy at +100 V and + 400V biased voltages. The electrometer readings for the respective biased voltages were carefully recorded, contributing to a thorough analysis of the LINAC's output constancy. The procedure was repeated for the 16 MV photon beam energy. The temperature and pressure were recorded using a digital traceable device with both thermometer and barometer embedded.

RESULTS AND DISCUSSION

Results

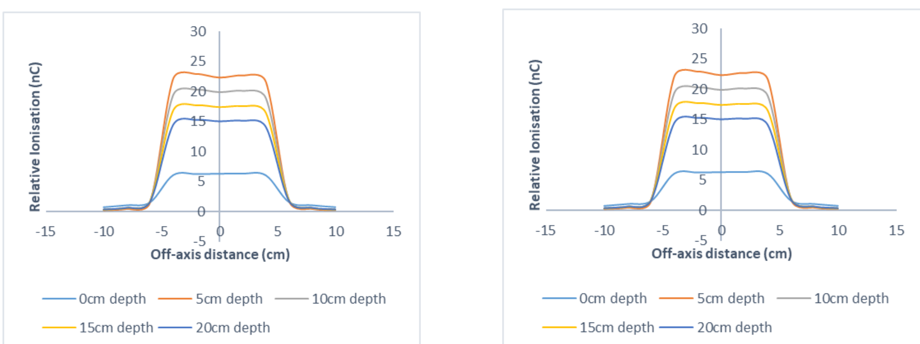
Photon Beam Dose Profile for 6 MV and 16 MV Energies

Figures 3 and 4 illustrate the photon beam profiles for 6 MV and 16 MV energies, respectively measured using a 30 x 30 x 30 cm³ manual water phantom. The profiles were obtained at two field sizes of 10 x 10 cm² and 15 x 15 cm² with a constant SSD of 100 cm.



(a) (b)

Figure 3: Cross-Plane Beam Profile of 6 MV Photon Beam (a) 10 x 10 cm²; (b) 15 x 15 cm²



(a) (b)

Figure 4: Cross-Plane Beam Profile of 16 MV Photon Beam (a) 10 x 10 cm²; (b) 15 x 15 cm²

The results from Figures 3 and 4 demonstrate highly satisfactory beam profiles for both energies indicating uniform dose distribution and excellent beam flatness and symmetry. These findings confirm the reliability of the LINAC's photon beam delivery.

Beam Flatness and Symmetry Analysis

Tables 2 and 3 present an assessment of beam flatness and symmetry for the 6 MV photon beams respectively utilizing field sizes of 10 x 10 cm² and 15 x 15 cm² at depths ranging from 0 cm to 20 cm. The source-to-surface distance was 100 cm.

Table 2: Beam Flatness and Symmetry at Various Depths for 6 MV Photon Beam on the LINAC machine

Depth (cm)	Flatness (%)		Symmetry (%)	
	10 × 10 cm²	15 × 15 cm²	10 × 10 cm²	15 × 15 cm²
0	2.02	2.22	0.53	0.93
5	1.72	2.34	0.25	0.96
10	0.88	1.39	0.31	0.57
15	1.81	2.00	0.78	0.70
20	2.22	2.04	0.48	0.86

Table 3: Beam Flatness and Symmetry at Various Depths in the Manual Water Phantom for 16 MV on the LINAC machine

Depth (cm)	Flatness (%)		Symmetry (%)	
	10 × 10 cm²	15 × 15 cm²	10 × 10 cm²	15 × 15 cm²
0	2.36	1.25	0.84	0.67
5	2.42	2.55	0.93	0.44
10	1.98	2.15	1.04	0.25
15	2.27	1.62	0.92	0.56
20	2.28	1.55	0.36	0.33

Tables 2 and 3 provide a detailed description of the beam performance across various depths and filed sizes, enabling evaluation of beam uniformity, dose distribution consistency and the LINAC reliability.

Measurement of Photon Beam Output Factors

The output factors of 6 MV and 16 MV photon beam energies were measured at a field size of 10 x 10 cm^2 using the water phantom. The measurements were taken at three biased voltages (+300 V, +100 V and -300 V) and a constant dose rate of 400 MU/min. Table 4 provides the measured output factors of 6 MV and 16 MV photon beam energies. This shows whether or not the dose delivered to the patient in each fraction, is constant and nominally accurate to the expected prescribed dose.

Table 4: Photon output factors of 6 MV and 16 MV photon beam energies

Photon Beam Output Factors (nC)			
Beam Energies	**+300 V**	**+100 V**	**-300 V**
6 MV	-16.73	-16.61	16.77
	-16.72	-16.57	16.74
	-16.70	-16.56	16.72
	-16.71	-16.58	16.72
	-16.72	-16.59	16.72
	-16.72	-16.59	16.72
	-16.72	-16.59	16.73
	-16.73	-16.59	16.72
16 MV	**-19.56**	**-19.28**	**19.59**
	-19.56	-19.28	19.59
	-19.56	-19.27	19.58
	-19.56	-19.27	19.58
	-19.56	-19.28	19.58
	-19.56	19.28	19.58

DISCUSSION

The study thoroughly examined key photon beam parameters, such as symmetry, flatness, and output factors for 6 and 16 MV photon energies, highlighting the importance of precise and uniform radiation delivery in clinical settings. The primary objective was to assess the accuracy and consistency of radiation dose delivery by the Varian Clinac iX Linear Accelerator (LINAC) at Komfo Anokye Teaching Hospital (KATH) under various conditions using solid and water phantoms across different field sizes and depths.

The flatness values obtained in this study, as shown in Table 2, were within the manufacturer's specifications of 3 %. The average flatness was 1.86 % for 6 MV and 2.04 % for 16 MV. When compared to the commissioning data of 2.35 % for 6 MV and 1.91 % for 16 MV, the flatness for 6 MV was lower as compared to the commissioning data, while the flatness for 16 MV was slightly higher by ±0.07 %. Despite this increase, the ±0.07 % deviation for 16 MV is within the ±1 % tolerance specified by the AAPM Task Group 198 Report (Goodall, Harding, Simpson, Alexander & Morgan, 2015), indicating that LINAC's performance remains satisfactory. Symmetry values, shown in Table 3, also met the manufacturer's 2 % specification. The study recorded average symmetry values of 0.64 % for 6 MV and 0.63 % for 16 MV. These deviated from the commissioning data of 0.30 % for 6 MV and 0.32 % for 16 MV.

This study's flatness and symmetry values were compared with the Bangladesh Atomic Energy Commission (BAEC) study on

6 MV Medical Linac. The BAEC study reported flatness ranging from 7.25 % to 9.4 % and symmetry between 1.73 % and 3.82 % (Roy *et al*., 2021), while this study found flatness between 0.88 % and 2.22 %, and symmetry between 0.25 % and 0.78 %, indicating superior beam uniformity.

The photon beam output factor values for 6 MV and 16 MV energies, as shown in the Table 4, demonstrate a consistent trend across different biased voltages (+300 V, +100 V, -300 V). Ideally, these output factors should be identical across the various voltages, as this would indicate consistency in beam performance. However, slight variations are observed, which is common in clinical settings due to equipment conditions including linear accelerator instability, beam transport and collimation issues, detector and dosimetry inaccuracies, phantom setup discrepancies, electrical and environmental factors and inadequate quality assurance and maintenance. For the 6 MV energy, the output factors show minimal variations across the different voltage levels, while the 16 MV energy demonstrates slightly higher consistency. The overall output factor for 6 MV is 16.72 nC, which is slightly below the commissioned value of 16.73 nC, representing a ±0.06 % deviation. For 16 MV, the output factor is 19.56 nC, slightly above the commissioned value of 19.44 nC, with a deviation of ±0.60 %. While the 16 MV output factor is higher than the commissioned data, it remains within the ±1 % tolerance specified by the AAPM Task Group 198 Report (Goodall, Harding, Simpson, Alexander & Morgan, 2015). This confirms that the outputs have not changed within a reasonable tolerance. Maintaining precise output factors shows an overall confidence that the patient dose during each fraction of the treatment is constant and nominally accurate to the expected prescribed dose.

The high degree of beam symmetry and flatness observed indicates that the KATH LINAC is performing reliably, which is vital for patient safety and treatment efficacy. Consistent and accurate radiation delivery is essential for achieving the desired therapeutic outcomes, particularly in complex treatments where precision is paramount. These results also reinforce the importance of routine quality control checks to ensure that the LINAC continues to operate within the required parameters. The study was limited by the malfunction of the automated 3D water phantom, which restricted comparative analysis with the 2D manual phantom, potentially overlooking nuanced insights into LINAC performance. The findings may not be representative of all LINAC machines or clinical environments. Despite limitations, the research demonstrates that KATH's Varian Clinac iX LINAC operates within specified tolerances, guaranteeing precise radiation delivery.

CONCLUSION

The study reveals outstanding performance of the LINAC, delivering photon beams with exceptional precision and uniformity across various field sizes and depths for 6 MV and 16 MV energies. Beam flatness, symmetry, and output measurements align remarkably with baseline commissioning data, affirming the LINAC's clinical reliability. These critical beam profile and output measurements are vital for achieving radiotherapy's primary objective: precise dose delivery to target volumes while protecting critical organs. This research highlights the crucial role of regular quality control in maintaining the accuracy and efficacy of radiotherapy treatments, ensuring optimal patient outcomes.

RECOMMENDATIONS

To ensure optimal LINAC performance, annual quality control tests are strongly advised. Future research should integrate 3D automated water phantoms for enhanced comparisons, bolstering quality assurance and patient outcomes.

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