An improved method for analyzing the output stability of medical LINAC based on planar dose (Postprint)

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Abstract

The absolute dose difference of the isocenter position at different times was used to evaluate the stability of the medical linear accelerator (LINAC). To eliminate the drawback of point dose lacking statistical significance and to investigate the output stability of low-weight segments related to intensity-modulated radiotherapy (IMRT), a modified method for evaluating LINAC stability based on planar dose combined with the gamma method was proposed. Using a commercially available two-dimensional ionization chamber, a set of planar doses with dose gradients ranging from 2 cGy to 100 cGy were obtained. The gamma method was then adopted to analyze the dose difference between reference data and evaluated data at each dose level. The results demonstrated that the improved method based on planar dose for analyzing the output stability of the medical LINAC was feasible and efficient, and suggested that reverse optimization should be aborted in clinical practice when the segment weight related to IMRT is below 10 MU.

Full Text

Preamble

An Improved Method for Analyzing the Output Stability of Medical LINAC Based on Planar Dose

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Abstract: The absolute dose difference at the isocenter position across different time points has traditionally been used to evaluate the stability of medical linear accelerators (LINACs). To overcome the limitation of point dose measurements lacking statistical significance and to investigate the output stability of segments with small weight in intensity-modulated radiotherapy (IMRT), we propose a modified method for evaluating LINAC stability based on planar dose combined with the gamma method. Using a commercially available two-dimensional ionization chamber, we obtained a series of planar doses with dose gradients ranging from 2 cGy to 100 cGy. The gamma method was then applied to analyze dose differences between reference and evaluated data at each dose level. The results demonstrated that the improved planar dose-based method for analyzing medical LINAC output stability is feasible and efficient, and suggests that reverse optimization should be aborted clinically when the segment weight related to IMRT falls below 10 MU.

Keywords: Planar dose; Gamma method; Medical LINAC; Output stability
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Introduction

Monitoring the output stability of medical LINACs constitutes a critical component of radiotherapy quality assurance. Current clinical practice for daily/weekly LINAC output stability checks follows procedures outlined in International Atomic Energy Agency (IAEA) Report No. 227 [1], which evaluates stability based on dose differences at the isocenter point across different time points. However, with the clinical implementation of new dose measurement equipment, point dose measurements reveal a significant drawback: they cannot reflect planar dose output stability and lack statistical significance. This limitation becomes particularly pronounced in intensity-modulated radiotherapy (IMRT), where planar dose evaluation for segments with small weight is crucial.

The gamma method, introduced by Low et al. [2], has become the most widely accepted approach and has been extensively adopted by numerous research groups [3–5]. In this paper, we propose a modified evaluation method for medical LINAC stability that employs the gamma method for planar dose verification to assess output stability. This research forms part of the Advanced/Accurate Radiotherapy System (ARTS) [6–12], a precision radiation treatment planning and quality assurance system project developed by the FDS Team [13–19].

Materials and Methods

A. LINAC and MatriXX Measurements were conducted using a 6 MV photon beam from an XHA600D LINAC (SHINVA, China) Figure 1: see original paper. The maximum dose depth was determined to be 1.5 cm underwater using a three-dimensional Blue Water Phantom (IBA, Germany). The I'mRT MatriXX (IBA, Germany) Figure 1: see original paper device comprises a two-dimensional array of 1020 vented parallel-plate ionization chambers arranged in a 32 × 32 grid with a center-to-center distance of 7.62 mm, covering an active area of 24 cm × 24 cm. The MatriXX was positioned using the LINAC field light, with a built-in beam buildup of approximately 3 mm. Additional beam buildup was provided by placing 30 cm × 30 cm RW3 Solid Water (Sun Nuclear, USA) layers with a thickness of 1.2 cm on the MatriXX surface. The LINAC gantry angle was set to 0 degrees with a source-to-surface distance (SSD) of 100 cm.

B. Calibration and Measurement

1. Calibration Following international standards [1], the LINAC output was calibrated such that 100 MU corresponded to 100 cGy at SSD = 100 cm, 10 cm × 10 cm field size, temperature T = 24.6°C, and pressure P = 999.7 Pa, using a cylindrical ionization chamber with 0.125 cm^3 air volume (PTW TM 31010 S/N03422) at the maximum dose depth (1.5 cm under solid water for 6 MV photons).

The MatriXX was placed under measurement conditions for 30 minutes to enable background correction. Solid water with 1.2 cm thickness was added to the surface (the device had a 3 mm beam buildup). At each MU level, the average value was calculated for the central four pixels. The cylindrical ionization chamber measured the absolute dose, after which the calibration scaling factor k was calculated and stored in the Omni I'm RT software.

2. Data Measurement Under radiation measurement conditions (SSD = 100 cm, field size: 10 cm × 10 cm), following 30 minutes of LINAC warm-up (period 1), various weights were irradiated onto 1.2 cm solid water at 1 MU, 2 MU, 3 MU, 5 MU, 10 MU, 20 MU, 40 MU, 50 MU, and 100 MU. Planar absolute and relative doses were obtained using MatriXX. For each MU level, more than 10 planar dose measurements were collected and averaged to serve as reference data for gamma analysis. After maintaining power for 8 hours (period 2), the same protocol was repeated, and the average planar dose served as evaluated data.

To investigate beam uniformity, a 28 cm × 28 cm field size with 100 MU was used to cover the 24 cm × 24 cm active area (maximum field). Flatness and symmetry serve as key performance indicators of beam dose distribution. According to International Electrotechnical Commission (IEC) standards, beam field flatness and symmetry should be within $±$3%. Ten different positions along both

X and Y axes were selected to verify flatness and symmetry of the maximum field. Table 1 demonstrates that all positions maintained flatness and symmetry within $±$3% with relatively uniform dose distribution and no obvious noise points, confirming that MatriXX data were reliable for dose verification.

C. Gamma (γ) Method The gamma method primarily performs dose verification by analyzing differences between reference and evaluated data. The method is expressed by the formula:

$$\gamma(r) = \min_{r'} \left\{ \sqrt{\left(\frac{\Delta r(r, r')}{\delta r_0} \right)^2 + \left(\frac{\Delta D(r, r')}{\delta D_0} \right)^2} \right\}$$

where: - ΔD represents the dose difference between reference and evaluated data - Δr represents the spatial distance between reference and evaluated data points - δr_0 is the distance-to-agreement tolerance, typically preset to 3 mm/2 mm in clinical practice - δD_0 is the dose difference tolerance, typically preset to 5%/3% in clinical practice

The pass-fail criterion for the gamma index at any point is: pass when $\gamma(r) \leq 1$, fail when $\gamma(r) > 1$. The distribution of $\gamma(r)$ values across all evaluated points determines the overall pass rate, calculated as the number of passing points divided by the total number of evaluated points. A pass rate exceeding 95% indicates good agreement between two planar dose distributions [20, 21].

Since the resolution of evaluated data was limited and the gamma method requires at least 1 mm data resolution, we implemented dose interpolation and comparison using Microsoft VC++ according to formula (1). A tolerance of 3%/3 mm was selected. The program implementation flowchart is shown in [Figure 2: see original paper].

Program Steps: 1. Input data exported from Omni I'm RT in ".txt" format 2. Interpolate evaluated data from 32$\times 32 to 320 \times$320 resolution 3. Calculate gamma values for each point in the evaluated data 4. Record pixel numbers with values less than or equal to 1 5. Calculate the pass rate of the evaluated data

Results

A. LINAC Output Stability for Different MU Levels Under radiation conditions of SSD = 100 cm, 10 cm × 10 cm field size, temperature T = 24.6°C, pressure P = 999.7 Pa, and calibration factor ND = 1.026, the LINAC 100 MU output was calibrated to correspond to 100 cGy. A cylindrical ionization chamber ("pinpoint" chamber) measured output dose at 1.5 cm depth in solid water phantom. Table 2 presents the mean readings from 10 measurements and output differences for each MU level.

After MatriXX calibration, planar relative dose signals were collected using movie mode (collection time = 500 ms) and exported as ".txt" documents. The scaling factor k from absolute dose calibration was multiplied by the relative dose distribution to obtain planar absolute dose. Data from period 1 served as reference input for the gamma method program, while period 2 data served as evaluated data. The pass rate was then calculated. Table 3 shows absolute dose comparison results between the two periods for each MU gradient, where "pass" indicates similar or equivalent dose distributions and "fail" indicates obvious differences. A 3%/3 mm tolerance was applied in this study.

B. Segment with Small MU In clinical practice, IMRT employs segments with optimized fractional doses typically divided into several segments of different weights. This study investigated the output stability of segments with small MU. As shown in Table 4, although relative dose measurements for 2 MU showed good uniformity, when multiplied by scaling factor k (0.29) to obtain absolute dose distribution, the relative output dose error was calculated as: $[(24 \times 0.29) - 2]/2 \times 100\% = 248\%$. This demonstrates that segments with small MU fluctuate significantly from the calibrated dose.

Table 3 results indicate that small MU segments failed dose comparison: 1 MU, 2 MU, and 5 MU all failed. When segment weight exceeded 10 MU, dose error became acceptable. Cylindrical ionization chamber readings verified these results. In Figure 3, the X-axis represents measurement times and the Y-axis represents readout data. Period 1 represents measurements after LINAC warm-up. Output weights fluctuated severely below 10 MU and deviated from calibrated data, with the same instability trend observed in period 2. This suggests that small MU segments under 10 MU related to IMRT should not be used in clinical reverse optimization.

Discussion and Conclusion

This study proposes an improved evaluation method for medical LINAC output stability based on planar dose combined with the gamma method. A 10 cm × 10 cm field size was selected for gamma analysis to avoid out-of-field dose interference.

Output stability analysis using a two-dimensional ionization chamber yielded results consistent with those from cylindrical ionization chambers, demonstrating the method's feasibility and efficiency. Unlike IAEA-TRS277 recommendations, which evaluate LINAC output stability only at 100 MU, this method can assess stability at any MU level using point dose differences while reflecting planar dose stability with statistical significance. The study also reveals that output becomes unstable when IMRT-related segment weight falls below 10 MU, introducing significant errors.

The MatriXX measurement device includes dose uniformity correction, particularly for low doses, yet planar dose for small MU segments still deviates from actual LINAC output dose distribution. While Omni I'm RT software provides gamma analysis and simple linear interpolation, we implemented bilinear interpolation using Microsoft Visual C++ to achieve higher data resolution for evaluated data. Interpolated pixel values were calculated from contributions of surrounding pixels. Future studies should compare interpolation method precision and investigate long-term (e.g., monthly/yearly) LINAC output stability to better understand LINAC performance characteristics.

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Note: Figure translations are in progress. See original paper for figures.