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Original Research Article

A note on electrometer intercomparison: a routine quality assurance check

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ABSTRACT

Background: This study evaluates the accuracy of the Max-4000 and Model 206 electrometers in measuring ionization readings during radiation therapy dosimetry. The goal is to assess their performance and reliability to determine if they can provide interchangeable and reliable measurements. These comparisons are crucial to ensure accurate radiation dose delivery to patients, improving treatment outcomes and patient safety in clinical settings.
Methods: Measurements were conducted using a Varian TrueBeam Edge at different photon energies (6 MV, 6 FFF, 10 MV, and 10 FFF) and field sizes ranging from 3.0 to 30.0 cm. The setup included a solid water phantom with an ionization chamber positioned at 5 cm depth and a 95 cm source-to-surface distance. Both electrometers, ADCL calibrated, were compared for accuracy and precision using the Bland-Altman method, regression analysis, and correlation analysis.
Results: The stability of individual charge readings was within ±0.005% for all energies, field sizes, and electrometers. The Bland-Altman analysis showed a bias of -0.0282 [0.0158 to -0.0405, 95% confidence interval (CI)] with a correlation coefficient (R^2) of 0.999 ($p<0.001$) for 6 MV, -0.0345 [0.0283 to -0.0408, 95% CI] with an R^2 of 0.999 ($p<0.001$) for 6 FFF, -0.0373 [0.0305 to -0.0441, 95% CI] with an R^2 of 0.999 ($p<0.001$) for 10 MV, and -0.00454 [0.00360 to -0.0127, 95% CI] with an R^2 of 0.999 ($p<0.001$) for 10 FFF.
Conclusions: this study establishes a framework for comparing two ADCL electrometers using Bland-Altman analysis, linear regression, and mean absolute percentage error (MAPE).

Keywords: Electrometer, Comparison, MAPE

INTRODUCTION

Ensuring consistent and accurate dosimetry in clinical settings requires regular comparisons between electrometers calibrated by accredited dosimetry calibration laboratories (ADCL). This process, conducted using a linear accelerator and a calibrated ion chamber, is crucial for monitoring electrometer stability and maintaining high standards of measurement accuracy. Adhering to the ADCL's bi-annual calibration protocol is essential for the reliability of dosimetry equipment. Accurate dosimetry ensures the precise delivery of the prescribed radiation dose to the target area, maximizing treatment efficacy while minimizing damage to surrounding healthy tissues. This precision reduces the risk of side effects and long-term complications, enhancing patient safety and post-treatment quality of life. Conversely, inaccurate dosimetry can lead to underdosing, rendering treatment ineffective, or overdosing, causing unnecessary side effects. Standardized dosimetry is also critical for consistent and reproducible treatments, especially for patients undergoing multiple sessions or different phases of therapy. Adherence to dosimetry standards and guidelines mandated by regulatory agencies ensures the safety and effectiveness of radiation therapy practices. Accurate dosimetry supports the implementation and validation of advanced radiation therapy techniques, such as intensitymodulated radiation therapy (IMRT) and stereotactic body radiation therapy (SBRT), which rely on precise dose delivery for success. In conclusion, accurate dosimetry is essential in radiation therapy for ensuring the safe and effective delivery of radiation to the target area while minimizing unnecessary exposure to healthy tissues. Addressing potential sources of uncertainty and following strict calibration and quality assurance protocols enable clinicians to maintain high standards of measurement accuracy, improving patient outcomes. Intercomparisons are a valuable tool in radiation oncology to assess consistency between equipment and detect potential systematic differences. This study aimed to perform an intercomparison of electrometers.

METHODS

Two electrometers, the CNMC Model 206 (865 East Hagen Dr. Nashville, TN 37215, USA) and the Standard Imaging Max-4000 (Middleton, WI, USA), were used in our clinic to calibrate high-energy photon and electron beams according to AAPM TG51 addendum 1 guidelines. Although both electrometers are overly sensitive instruments for detecting small electrical currents, there are notable differences between them, as summarized in Table 1 and depicted in Figure 1.

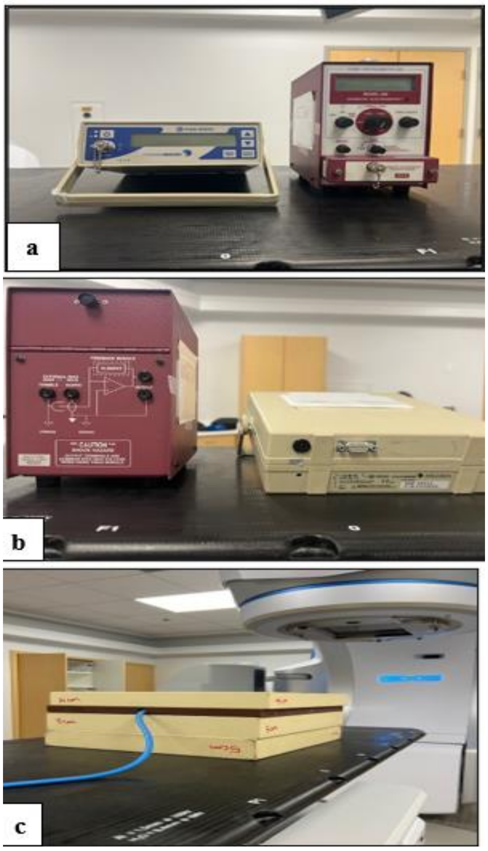


Figure 1: (a) Image of the CNMC Model 206 (b) standard imaging Max-4000, (c) along with the experimental setup used in this study.

To investigate the comparability of these two electrometers, we conducted measurements using a Varian TrueBeam linear accelerator (Varian Medical Systems, Palo Alto, CA, USA). The accelerator provided variable photon beam energies of 6 MV, 10 MV, 6 FFF, and 10 FFF. Simultaneously, charge was collected using a PTW 31010 ionization chamber with a volume of 0.6 cm^3 at a bias of -300V and 100% for the Max-4000 and CNMC, respectively, through a triaxial extension cable. All electrometers were operated in continuous mode, and the current was allowed to stabilize before the beam was turned on to avoid any leakage current. The ionization chamber was positioned at a depth of 5 cm in solid water, with a source-to-surface distance (SSD) of 95 cm. A total of 100 monitor units (MUs) were administered at a dose rate of 600 MU/min. The field size ranged from 3.0 to 28 cm. The experimental setup consisted of a solid water slab, 10 cm of solid water for backscatter, and the ionization chamber. The temperature and air pressure were monitored during the measurements to ensure precise correction of the results. To minimize statistical errors, three measurements were taken with each electrometer.

Statistical analysis

Statistical analysis was conducted by calculating the mean (standard deviation) for descriptive statistics. A paired t-test was utilized to compare charges measured by the CNMC and Max-4000. The percentage error was expressed as the percentage of each difference to its matched reference value. Accuracy was assessed by calculating the mean absolute percentage of error (MAPE) for each method.[1]

$$MAPE = \frac{1}{n}\sum_{i=1}^{n} \frac{|A_i - F_i|}{A_i} \quad (1)$$

Ai is the actual value.

Fi is the Forecast

N is the total number of observations

The MAPE criteria depicted in table 2 were considered accurate in this study. Correlation was calculated using Pearson's bivariate correlation. Linear regression analysis was used to calculate the percentage of variability in the charge measured with the CNMC and Max-4000, and a linear regression equation was developed. Bland-Altman plots were created, along with the mean difference and 95% limits of agreement (LOA), to show the relationship between the diverse types of charge measurements at various field sizes and energies. Statistical significance was defined as $\alpha<0.05$, and all tests performed were two-tailed. The Mann-Whitney U-test was used to compare two independent medians.

RESULTS

This study aims to compare the measurements of the Standard Imaging Max-4000 and the CNMC Model 206 electrometers using Bland-Altman analysis and linear regression. The measurements were taken using a TrueBeam system at various field sizes and energies (6 MV, 6 FFF, 10 MV, and 10 FFF). The high R^2 value from the linear regression shown in the electrometers heatmap (Figure 2) and the acceptable limits of agreement from the Bland-Altman analysis (Figure 3a, b, c, and d) indicate strong agreement between the Standard Imaging Max-4000 and the CNMC Model 206 electrometers. The differences between CNMC and SI values are typically within the range of 0.01 to 0.06, which is considered acceptable for clinical measurements.

The largest difference recorded is 0.06 (CNMC 10 FFF) compared to 17.38 (SI 10 FFF), which suggests a very slight deviation that still falls within the acceptable range for clinical measurements. Additionally, the bias, lower, and upper limits (shown in Table 4) suggest that the observed differences are within an acceptable range for clinical use, confirming the reliability of both electrometers for measurements in a clinical setting. Our goal was to compare the performance of two commonly used electrometers for radiation therapy dosimetry: the Standard Imaging Max-4000 and CNMC Model 206. We assessed the accuracy and precision of each electrometer by measuring ionization readings at various energy settings (6 MV, 6 FFF, 10 MV, and 10 FFF).

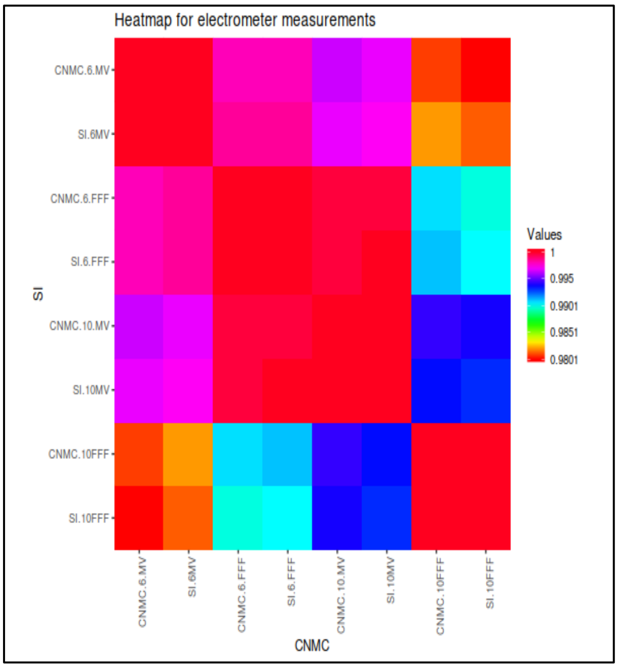


Figure 2: Heatmap for the measurements taken by electrometers, along with the calculated correlation matrix.

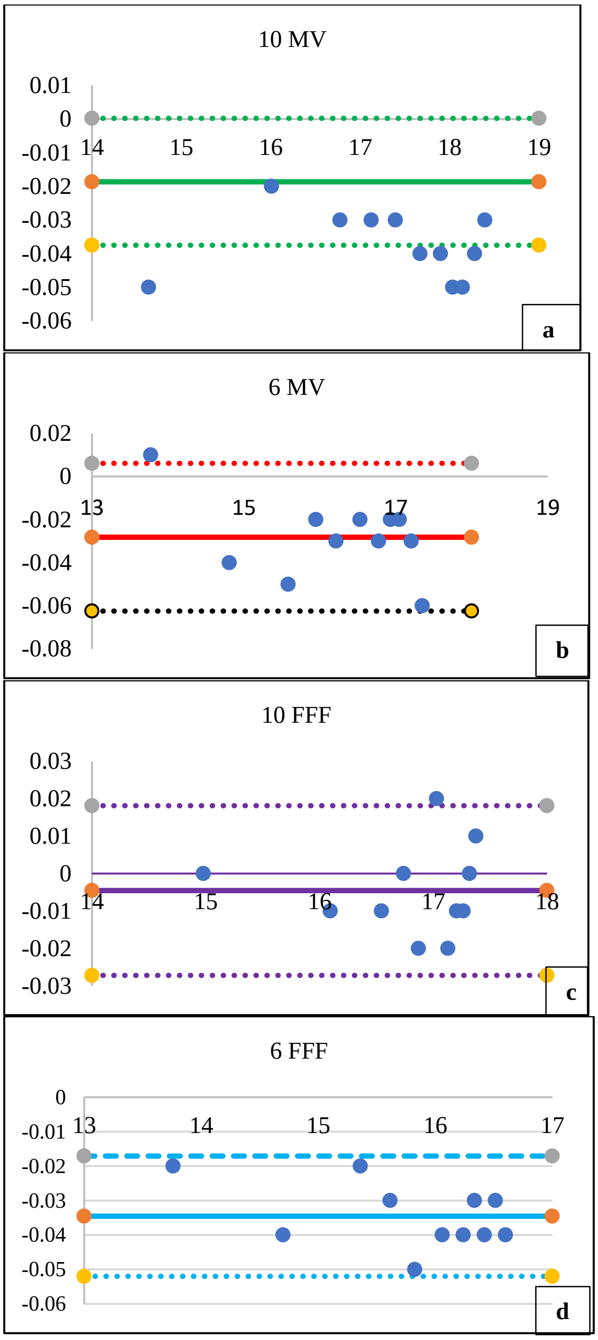
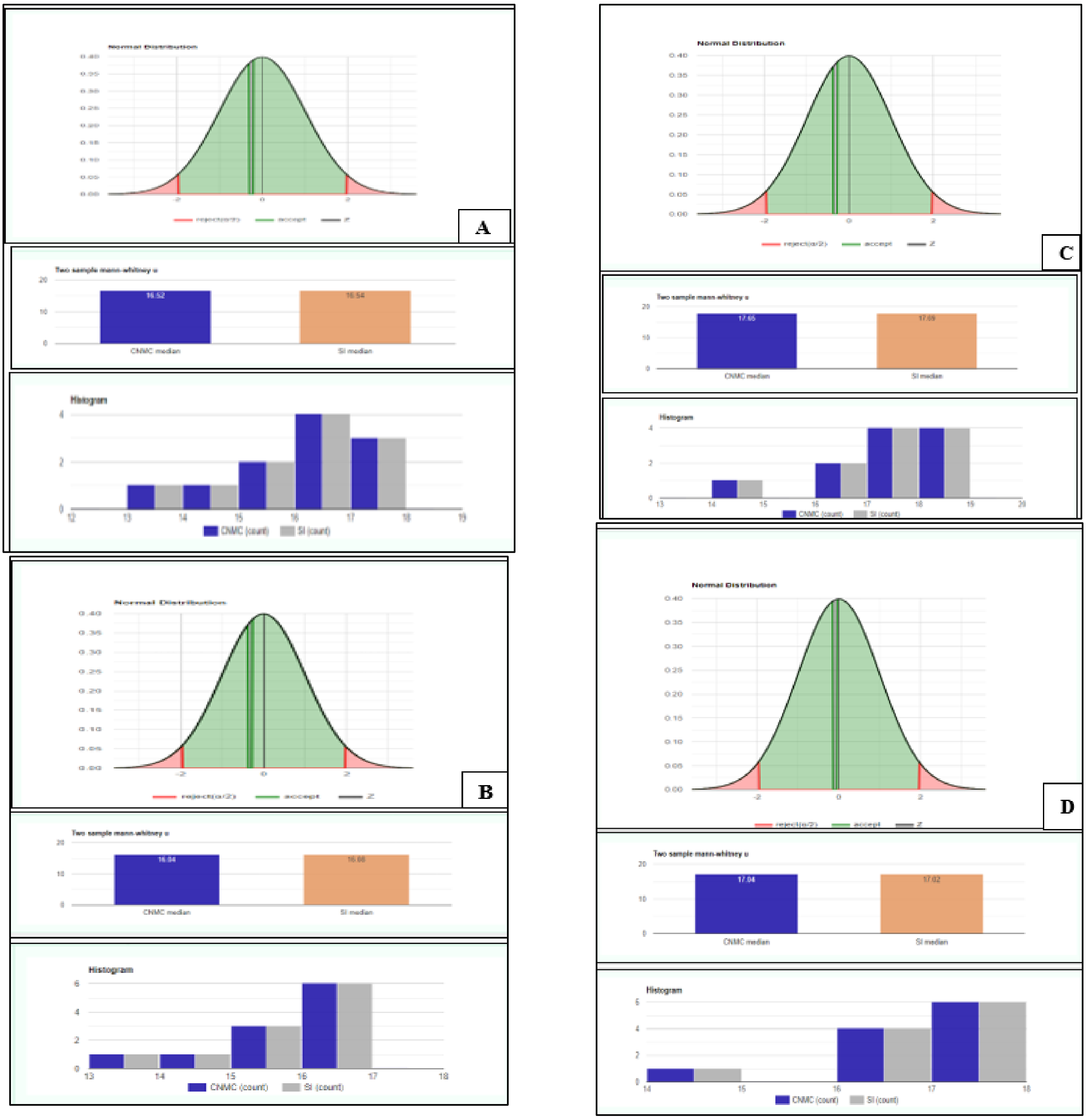


Figure 3 (a-d): Displays a Bland Altman plot, comparing the measured charges of two different electrometers: CNMC model 206 and Standard Imaging Max-4000. The solid lines represent the mean difference between the two electrometers, while the dashed lines represent the limits of agreement, calculated as the mean difference±1.96 standard deviations.

To determine if there were any differences in electrometer readings between the CNMC Model 206 and the Standard Imaging Max-4000 across different energy levels, a Mann-Whitney U test was conducted. Table 4 summarizes the descriptive statistics for each energy level.



Figures 4 (A-D): Demonstrate a strong correlation, normal distribution, and histogram between CNMC and SI electrometers for various charge values at different field sizes for 6 MV, 6FFF, 10 MV, and 10 FFF, respectively.

The results of the test for each energy level are as follows, for 6 MV, the Mann-Whitney U test indicated no significant difference in electrometer readings between the CNMC model 206 and the standard imaging Max-4000, with a U value of 56 and a p value of 0.7928. For 6 FFF, the Mann-Whitney U test also showed no significant difference in readings between the two electrometers, with a U value of 55 and a p value of 0.7427.

Similarly, for 10 MV and 10 FFF, the test results indicated no significant difference in readings between the CNMC model 206 and the Standard Imaging Max-4000, with U values of 55 and 58.5, and p values of 0.7477 and 0.9215, respectively. Based on these results, it can be concluded that there are no statistically significant differences in the electrometer readings between the CNMC model 206 and the standard imaging Max-4000 at the tested energy levels. The p values for all energy levels are above the conventional threshold of 0.05, indicating that any observed differences in readings are not statistically significant.

Therefore, both electrometers can be considered to provide comparable readings under the tested conditions.

The median measurement and normal distribution for all the energies considered are illustrated in figure 4.

We also calculated the mean absolute percentage error (MAPE) values, ranging from 0.059% to 0.22% across all tested energies.

Table 3: Displays of the bias, upper limit, and lower limit of agreement for electrometer measurements are shown for various photon energies.

Energies	Bias	Upper LOA	Lower LOA
6 MV	-0.0282	0.0077	-0.0641
6 FFF	-0.0345	-0.0162	-0.0530
10 MV	-0.0372	-0.0175	-0.0570
10 FFF	-0.0045	0.0192	-0.0283

Table 4: Mann-Whitney U Test and MAPE percentages for electrometers measurements at different energy settings and field size.

Energies	U	P value	MAPE %
6 MV	56	0.7928	0.185
6 FFF	55	0.7427	0.219
10 MV	55	0.7477	0.22
10 FFF	58.5	0.9215	0.059

These findings indicate high accuracy in measurement predictions for both electrometers. Overall, our study demonstrates the reliability of both the standard imaging Max-4000 and CNMC model 206 electrometers for radiation therapy dosimetry. We hope that these findings will contribute to the improvement of treatment accuracy and patient safety in this field.

DISCUSSION

The Max-4000 and Model 206 electrometers are both designed to meet stringent calibration standards, ensuring accurate dose measurements. Our experiments using a TrueBeam system demonstrated a high level of agreement between the two devices, as evidenced by linear regression analysis with R^2 values approaching 0.999. Bland-Altman analysis further confirmed that the differences in measurements between the electrometers were within acceptable ranges, indicating that both devices provide consistent and reliable measurements under identical conditions. This strong agreement supports their interchangeability in clinical settings.

We tested both electrometers at various energies (6 MV, 6 FFF, 10 MV, 10 FFF) and different field sizes, and both performed reliably across these diverse settings. This consistency is critical for maintaining accurate dosimetry across a range of treatment plans, highlighting the versatility and dependability of these electrometers in different clinical scenarios.

The Max-4000 and Model 206 electrometers differ in design and user interface, which can influence their use in clinical practice. The Max-4000's automatic zeroing feature simplifies the measurement process by eliminating the need for manual adjustments, thereby enhancing user convenience and efficiency. This feature allows for multiple measurements to be performed in quick succession without manual intervention. Conversely, the CNMC Model 206 requires mechanical zeroing, involving manual adjustment. While this may be less convenient, it provides greater control, which is preferred in precise measurement scenarios where exact zeroing is critical.

The automatic zeroing feature of the Max-4000 is designed to minimize noise by accounting for and subtracting background noise through internal electronics and software algorithms. This process provides a cleaner baseline for measurements, enhancing consistency by standardizing the zeroing process and reducing variability caused by manual adjustments. However, automatic systems can sometimes introduce electronic noise due to internal circuitry and software processing. The frequent recalibration of the baseline measurement mitigates this by reducing the impact of flicker noise, which is more prominent at low frequencies.

In contrast, mechanical zeroing allows for direct control over the zeroing process, potentially reducing noise introduced by electronic components. The effectiveness of this method, however, depends on the user's precision in zeroing the device. Manual adjustments can introduce variability and noise if not performed accurately, leading to inconsistencies. Moreover, mechanical systems can be more susceptible to environmental noise, such as vibrations or electromagnetic interference, if not adequately shielded or isolated.

The differences in sensitivity and measurement range between the two electrometers may influence the choice of device based on specific clinical requirements. These differences necessitate careful selection depending on the clinical context and specific measurement needs. Although both electrometers are designed to compensate for environmental factors, slight variations may exist in how each device adjusts for changes in temperature, pressure, and humidity. These variations can result in minor differences in raw readings, which must be calibrated and corrected to ensure accuracy. The Bland-Altman analysis revealed minimal and clinically insignificant differences between the Max-4000 and Model 206, supporting their interchangeability for routine dosimetric measurements. Low Mean Absolute Percentage Error (MAPE) values further indicate that both electrometers provide highly accurate dose measurements with minimal error, underscoring their reliability.

Despite the high level of agreement, several sources of uncertainty can still impact dosimetric accuracy. Calibration factors can introduce uncertainty into dose measurements, and even small calibration errors can affect dose delivery, potentially impacting treatment efficacy and side effects. Changes in temperature, pressure, and humidity can affect readings, requiring correction factors and careful monitoring. Energy fluctuations and setup inconsistencies can also influence dosimetry accuracy. Poor setup reproducibility can result in significant measurement errors. Additionally, errors in dose rate and field size determination contribute to overall uncertainty. Calibration stability and the inherent characteristics of measurement devices necessitate regular maintenance. To mitigate these uncertainties, regular calibration of ionization chambers and electrometers against Accredited Dosimetry Calibration Laboratory (ADCL) standards is essential to minimize device-specific uncertainties. Implementing strict environmental controls and applying correction factors can reduce the impact of variable conditions. Standardizing setups and training staff on best practices improve reproducibility. Regular verification and documentation of beam quality characteristics help identify and correct fluctuations. Conducting thorough uncertainty analysis, including statistical methods, ensures a better understanding and mitigation of potential errors.[3] Minimizing uncertainties is crucial for patient safety, reducing the risk of adverse effects, and improving overall treatment outcomes. Accurate dosimetry enhances patient quality of life post-treatment and ensures compliance with regulatory standards, thereby reducing the risk of legal and accreditation issues for healthcare facilities. This study demonstrates that the Max-4000 and Model 206 electrometers are comparable, with results falling within acceptable ranges. This consistency underscores the importance of regular intercomparisons and strict adherence to quality assurance protocols to maintain accurate dosimetry in clinical settings. The findings align with previous research and emphasize the significance of accurate and reliable measurements in ensuring optimal patient care and treatment outcomes.

CONCLUSION

The strong agreement between the Standard Imaging Max-4000 and the CNMC Model 206 electrometers, as demonstrated by the Bland-Altman analysis and linear regression results, suggests that both electrometers can be reliably used for clinical measurements. Regular intercomparisons and adherence to quality assurance protocols are essential for maintaining accurate dosimetry and ensuring the safety and efficacy of radiation therapy treatments.

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