sciendo
Polish Journal of Medical Physics and Engineering
The Journal of Polish Society of Medical Physics
ISSN 1898-0309, doi: 10.2478/pjmpe-2025-0024

September 2025
Vol 31, Issue 3

Scientific Paper

Evaluation of cross-calibration based on TRS-398 and TG-51 to modified electron beam calibration methods

Vibol Ban[1,2,BCD], Nelly Nelly[3,B], Fransisca Yulia Dimitri[3,B], Supriyanto Ardjo Pawiro[1,ADEF,*]

[1] *Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Indonesia, Depok, Indonesia*
[2] *Oncology and Radiotherapy Department, Luang Mè Hospital, Phnom Penh, Cambodia*
[3] *Department of Radiation Oncology, Siloam Hospitals TB Simatupang, Jakarta, Indonesia*
**Corresponding author: Supriyanto Pawiro; supriyanto.p@sci.ui.ac.id*

(received 14 December 2024; accepted 2 June 2025)

Abstract

Introduction: Accurate electron beam dosimetry is crucial for effective radiotherapy treatment. This study aimed to validate modified electron beam calibration methods through a comprehensive cross-calibration analysis against the established IAEA TRS-398 and AAPM TG-51 protocols.

Materials and methods: A Varian Trilogy linac with electron beam energy of 6, 9, 12, 15, and 18 MeV was used to perform dosimetric assessments using cylindrical (FC65-G and CC13) and parallel-plate (PPC40) ion chambers. The sequential method was employed for cross-calibration at 18 MeV, with each chamber alternatively serving as the reference and field chambers according to TRS-398 (yielding calibration correction factor $N_{TRS-398}$) and TG-51 (yielding calibration correction factor N_{TG-51}) protocols. The ratios of $N_{TRS-398}$ and N_{TG-51} compared to the calibration correction factors from country SSDL (N_{Co}) it ranged from 0.990 to 1.020. Absorbed doses to water per monitor unit (cGy/MU) were calculated at maximum absorption depths.

Results: For modified calibration methods, the values of $N_{TRS-398}$ and N_{TG-51} yielded absorbed dose values between 0.977-1.005 cGy/MU and 0.980-1.009 cGy/MU, respectively. Dose ratios of the modified methods compared to TRS-398 ranged from 0.982 to 1.010, while ratios compared to TG-51 varied between 0.985 and 1.021. The average absorbed dose to water using $N_{TRS-398}$ and N_{TG-51} ranged from 0.984-0.996 cGy/MU and 0.986-0.997 cGy/MU, respectively. The results were also compared with previous studies to demonstrate that the modified calibration methods closely align with the established protocols, with discrepancies within the IAEA's ±2% tolerance threshold.

Conclusions: The study highlights the importance of cross-calibration in ensuring the accuracy and reliability of modified electron beam calibration methods. These findings suggest that the modified approaches can serve as effective alternatives to traditional protocols, potentially enhancing dosimetric precision and flexibility in clinical radiotherapy settings.

Keywords: modified calibration, IAEA TRS-398, AAPM TG-51, cross-calibration, absorbed dose

Introduction

Radiotherapy's effectiveness hinges on the precision of electron beam dosimetry, which is underpinned by standardized protocols issued by leading organizations such as in North America, AAPM TG-51 is a broadly used protocol, while DIN 6800–2 is more widespread in European countries, and IAEA TRS-398 is more widely used worldwide[1]. These protocols are pivotal in standardizing absorbed dose to water, a critical factor in ensuring the accurate delivery of therapeutic radiation.

IAEA TRS-398[2] and AAPM TG-51[3] protocols delineate specific guidelines for reference dosimetry, advocating for the employment of either cylindrical or parallel-plate ionization chambers. These guidelines establish energy thresholds for applying cylindrical chambers, stipulating a minimum R_{50} value of 4.0 cm for TRS-398 and 2.6 cm for TG-51. This is because utilizing at low energy, one cylindrical chamber can yield a fluence perturbation correction factor of up to 5%[4]. Due to their architectural design, parallel-plate chambers effectively mitigate perturbation effects by curbing electron scatter[5]. With a focus on low-energy electron beam measurements, international protocols lean towards parallel-plate chambers to counteract fluence perturbation effects due to their thin, water-equivalent windows. Conversely, the significant fluence

Authors' contribution: A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

correction factor for cylindrical chambers at low energies is traditionally viewed as a source of increased uncertainty[6,7]. However, emerging literature[6,8-10] suggests that perturbation correction variability for cylindrical chambers might be overestimated, and recent studies imply that their stability might warrant usage across all electron beam energies. It is necessary to regularly review the progress made in dosimetry to achieve higher precision and accuracy in radiation dosimetry.

From current formalism, Muir and Roger[11] have advocated for modified electron beam calibration, eliminating the need for correction of gradient factors, and updated beam energy quality factors ($k_Q^{'}$) by Monte Carlo calculations, and promoting the application of cylindrical chambers across all energy levels, thereby harmonizing electron beam dosimetry more closely with photon beam procedures. Muir's research[6], utilizing an Elekta Precise accelerator and six difference ion chambers, examines the effectiveness of cylindrical chambers for low-energy electron beams. The study extends electron beam energies between 4 MeV and 22 MeV, employing 10×10 cm^2 applicators, and expanding to 20×20 cm^2 for energies at 18 MeV and 22 MeV. His findings corroborate the effectiveness of cylindrical chambers at these varied intensities, recommending their use for reference dosimetry irrespective of the electron beam energy levels. Further examination[8] of a modified formalism of electron beam against TRS-398 protocol was conducted using two Elekta linear accelerators (Synergy Platform and Versa HD) and a selection of ionization chambers including PTW-30013, IBA-CC13, Exradin-A1SL, and Exradin-A11. In their study, the comparative analysis results revealed that the dosage ratios between TRS-398 standard and the modified formalism range from 1.000 to 1.014, indicating a promising alignment with established protocols. A subsequent study involving two Elekta linear accelerators and three different ion chambers demonstrated that average absorbed dose ratios using the modified formalism vis-à-vis the present protocols (TRS-398 and TG-51) were within the IAEA's tolerance threshold of ±2%, recording average ratios of 1.004 and 1.009, respectively[9]. Moreover, a comprehensive multi-institutional analysis, involving seven institutions and utilizing a mix of cylindrical and parallel-plate chambers, examined the modified calibration process in contrast to the TRS-398 and TG-51 guidelines[10]. The results indicated ratio of absorbed dose ranges from 0.980-1.019 for Modified/TRS-398 and 0.981-1.019 for Modified/TG-51, further reinforcing the adaptability and reliability of the modified calibration method. These findings hint that modified calibration methods could serve as a feasible alternative to the current standards.

While existing studies have laid a robust foundation, affirming the potential of modified calibration methods, a comprehensive exploration of the cross-calibration process-involving calibrating a user chamber by directly comparing it with a reference chamber that has already been calibrated[12], specifically, its impact on the accuracy and clinical feasibility of modified calibration – remains less explored. This study aims to bridge this gap by conducting a detailed cross-calibration analysis, utilizing cylindrical and parallel-plate chambers endorsed by TRS-398 and TG-51 to critically assess the accuracy and practicality of modified calibration methods for electron beam dosimetry.

Materials and methods

A Linac Varian Trilogy located at the Radiation Oncology Department of Siloam Hospitals TB Simatupang was used to provide a sequence of electron beams (energies: 6, 9, 12, 15, and 18 MeV) to a water phantom during dosimetric assessments. The applicator employed for all measurements was standardized to an area of 10×10 cm^2. The ionization chambers, sourced from IBA company, included the FC65-G, CC13, and PPC40 models with calibration correction factors from country SSDL. The chambers were placed at reference depths (z_{ref}), which were protocol-dependent and will be further discussed at the designated point of measurement (POM) in the next sections. The POM is crucial because it varies between protocols and affects dose measurement accuracy.

Each ionization chamber was connected to an electrometer set at voltage levels of ±300V and +100V, with the procedure adhering to a standard dosage of 100 monitor units (MU) administered at a 400 MU/minute rate. The beam quality symbolized as R_{50} within the frameworks of both TG-51 and TRS-398, serves as the foundational parameter for determining the clinical reference dosimetry depth (z_{reg}). The TG-51 protocol integrates elements such as $k_{R_{50}}$, k_{ecal} and P_{gr}^{Q} whereas TRS-398 specifies beam quality using k_{Q,Q_0}. To establish the ionization chamber's precise positioning within the phantom, the formula $z_{ref} = 0.6R_{50} - 0.1(cm)$ was utilized. Additional considerations regarding POM, as dictated by the nuances of the modified calibration and TRS-398 and TG-51 formalism, are delineated in subsequent sections. The correction of ionization chamber's initial readings (M_{raw}) was accomplished using the specified formula:

$$M_Q = M_{raw} P_{TP} P_{ion} P_{pol} P_{elec} \quad (1)$$

In this equation, M_Q represents the chamber's corrected reading, adjusted for environmental and equipment variables. P_{TP} accounts for temperature and pressure variations, ensuring that readings reflect standard conditions. P_{ion} corrects for ion recombination, a phenomenon that can affect the accuracy of dose measurements. P_{pol} addresses any discrepancies due to the polarity of the applied voltage, compensating for differences in response between positive and negative charges. And P_{elec} is the electrometer calibration factor. Each of these correction factors depends on the protocols.

Cross-calibration

For high-energy electron beams, TRS-398 and TG-51 recommend cross-calibration. In this study, the sequential method was applied at 18 MeV to derive calibration correction factors ($N_{TRS-398}$ and N_{TG-51}) using the respective protocols. As shown in **Figure 1**, the roles of the three ion chambers (PPC40, FC65-G, and CC13) were alternated as reference and field chambers.

This systematic setup enabled the precise determination of calibration correction factors, with beam quality conversion factors detailed in subsequent sections.

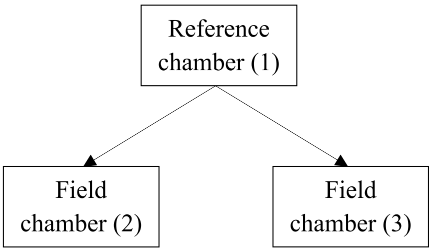

Figure 1. Diagram of alternative roles of the three ion chambers (PPC40, FC65-G, and CC13) for cross-calibration.

For TRS-398, the cross-calibration correction factor is calculated by:

$$N^{x}_{D,w,Q_{cross}} = \frac{M^{ref}_{Q_{cross}} k^{ref}_{Q_{cross},Q_0}}{M^{x}_{Q_{cross}} k^{x}_{Q_{cross}}} N^{ref}_{D,w,Q_0} \tag{2}$$

In this study, $k^{x}_{Q_{cross}}$ was included in the equation since $N^{x}_{D,w,Q_{cross}}$ was employed for computing the absorbed dose to water in modified calibration method.

The equation calculates the calibration correction factor following TG-51 protocol:

$$(N^{60Co}_{D,w})^{field} = \frac{\left(MP^{Q}_{gr} k'_{R_{50}} k_{ecal} N^{60Co}_{D,w}\right)^{ref}}{\left(Mk'_{R_{50}} k_{ecal}\right)^{field}} \tag{3}$$

IAEA TRS-398 protocol

Under the TRS-398 protocol, cylindrical chambers were positioned at half their inner radius (0.5 r_{cyl}) below the reference depth, while parallel-plate chambers' effective point of measurement (EPOM) matched z_{ref}, with PPC40's front window at 1.0 mm thickness. The absorbed dose calculation adhered to the formula:

$$D_{w,Q} = M_Q N_{D,w,Q_0} K_{Q,Q_0} \tag{4}$$

M_Q is the corrected reading, N_{D,w,Q_0} is calibration correction factor, and k_{Q,Q_0} is the beam quality conversion factor relies on R_{50}. The values of k_{Q,Q_0} can be found in IAEA TRS-398 in Table 7.III[2].

AAPM TG-51 protocol

Following the AAPM TG-51 protocol, the calculation of absorbed dose to water was conducted utilizing:

$$D^{Q}_{W} = Mk_Q N^{60Co}_{D,W} \tag{5}$$

with M is the completed reading correction from an ion chamber, a cobalt-60 calibration coefficient factor ($N^{60Co}_{D,W}$), and the beam quality conversion factor, k_Q, is required to convert $N^{60Co}_{D,W}$ to that interest beam quality, Q.

$$k_Q = P^{Q}_{gr} k_{R50} \tag{6}$$

P^{Q}_{gr} is exclusively applied with cylindrical chambers to mitigate gradient effects at designated reference levels. Its values are contingent upon the air cavity's dimensions and ionization gradient at the measurement point within the user's electron beam. This is how P^{Q}_{gr} is calculated:

$$P^{Q}_{gr} = \frac{M_{raw}\left(d_{ref} + 0.5r_{cav}\right)}{M_{raw}\left(d_{ref}\right)} \tag{7}$$

where k_{R50} is unique to quality-dependent ionization chambers and is derived from the absorbed dose calibration factor and the quality of the user's beam (Q):

$$k_{R50} = k'_{R50} k_{ecal} \tag{8}$$

The photon-electron conversion factor (k_{ecal}) was established for a particular model of ion chamber. The calculation of k'_{R50} was performed utilizing the subsequent equations:

$$k'_{R_{50}}\left(cyl\right) = 0.9905 + 0.0710e^{\left(-\frac{R_{50}}{3.67}\right)} \tag{9}$$

$$k'_{R_{50}}\left(pp\right) = 1.2239 - 0.145\left(R_{50}\right)^{0.214} \tag{10}$$

The placement of cylindrical chamber was placed at z_{ref} with its central axis, and the parallel-plate chambers were positioned with their POM at z_{ref}. PPC40's EPOM was 1.0 mm (physical thickness of the front window).

Modified calibration

The modified calibration method integrated the gradient effect correction factor P^{Q}_{gr} into the beam quality conversion factors through Monte Carlo calculation. This integration is manifested in the absorbed dose equation:

$$D_w = Mk'_Q k_{Q,ecal} N^{Co}_{D,w} \tag{11}$$

where M is fully corrected charge readings and calibration correction factor, ($N_{D,w}$), is derived from the calibration. A revised notation was introduced employing subscripts Q instead of $R_{50}$to signify the implicit inclusion of P^{Q}_{gr}. k'_Q represents the updated beam quality conversion factors, determined through the following process:

$$k'_Q\left(cyl\right) = a + b \times R_{50}^{-c} \tag{12}$$

$$k'_Q\left(pp\right) = a + b \times e^{-R_{50}/c} \tag{13}$$

Parameter a, b, and c are the parameter fitting for each ion chamber type shown in **Table 1** and **Table 2**. The values for k'_Q and $k_{Q,ecal}$ (updated photon–electron conversion factors) are shown in **Table 3**. Cylindrical chambers were placed at z_{ref} with their central axis, and parallel-plate chambers were placed at z_{ref} with its POM. The EPOM for PPC40 was 1.39 mm.[11]

All absorbed dose to water measurements at the depth of z_{ref} were transformed to the absorbed dose at the maximum depth (z_{max}) by:

$$D_{w,Q}\left(z_{\max}\right) = \frac{100 \times D_{w,Q}\left(z_{ref}\right)}{PDD_{z_{ref}}} \tag{14}$$

Table 1. Parameter of power fit of cylindrical chambers for calculating k'_Q based on Muir and Roger[11].

Ion chamber	Power fitting coefficient			
	a	b	c	RMSD (%)
FC65-G	0.971	0.113	0.680	0.13
CC13	0.926	0.129	0.279	0.10

Table 2. Parameter of exponential fit of parallel-plate chambers for calculating k'_Q based on Muir and Roger[11].

Ion chamber	Exponential fitting coefficient			
	a	b	c	RMSD (%)
PPC40	0.985	0.130	3.510	0.12

Table 3. Beam quality conversion factors for modified calibration methods.

Energy (MeV)	R_{50} (cm)	k'_Q		
		FC65-G	CC13	PPC40
6	2.41	1.033	1.027	1.050
9	3.63	1.018	1.016	1.031
12	5.07	1.008	1.008	1.016
15	6.37	1.003	1.003	1.006
18	7.67	0.999	0.999	1.000
Q_{ecal}	7.50	$k_{Q,ecal}$		
		0.904	0.904	0.900

Analysis

Measurements taken at the depth reference point were converted to the maximum depth dose using percentage depth dose (PDD). Modified calibration measured the absorbed dose with calibration correction factors from cross-calibration ($N_{TRS-398}$ and N_{TG-51}) while standard protocols were calculated with calibration correction factors from country SSDL (N_{Co}). The analysis involved calculating the comparison of modified calibration to TRS-398 and TG-51 results. The dose ratio of modified calibration using $N_{TRS-398}$ and TRS-398 using N_{Co}, is denoted as $Modified_{N_{TRS-398}} / TRS-398_{N_{Co}}$ (both methods used the same chamber). The same way but applied with TG-51 is denoted as $Modified_{N_{TG-51}} / TG-51_{N_{Co}}$. Modified calibration results were evaluated using the dose ratio and discrepancy.

Results

Calibration correction factor from cross-calibration

By applying a sequential cross-calibration method at 18 MeV electron beam using FC65-G, CC13, and PPC40 ionization chambers, this research meticulously quantified calibration correction factors derived from cross-calibration based on TRS-398 and TG-51 protocols. The outcomes are depicted in **Table 4**. The analysis highlighted a tight range of correction factor ratios from 0.990 to 1.020 compared to standards set by the country SSDL, showcasing remarkable precision across various chamber configurations and calibration protocols. The highest ratio of calibration correction factor from a cross-calibration based on TG-51 to calibration correction factor from country SSDL is 1.020 where PPC40 was the reference chamber and FC65-G was the field chamber, whilst vice-versa of the two chambers' roles produced the lowest ratio which is 0.990.

Results of absorbed dose to water for modified calibration

Absorbed dose to water per monitor unit (cGy/MU), as illustrated in **Table 5** indicates that the cross-calibration based on TRS-398 and TG-51 yields remarkably similar trends in absorbed dose to water via modified calibration. The difference compared with the standard dose unit (1 cGy/MU) in the absorbed doses when using $N_{TRS-398}$ ranged from 0.977--1.005 cGy/MU with a discrepancy between -2.3% to 0.5% with the greatest deviation observed at 12 and 15 MeV for all chambers, and FC65-G (PPC40 as the reference chamber) has the lowest absorbed dose (0.977 cGy/MU). The only dose that exceeds the standard dose unit is PPC40 (CC13 as the reference chamber) which is 1.005 cGy/MU at 18 MeV.

In comparison, using N_{TG-51} resulted in absorbed dose to water for all studied depths between 0.980 cGy/MU and 1.009 cGy/MU with a discrepancy ranging from -2.0% to 0.9% with the most notable positive discrepancy at 6 MeV measuring by the FC65-G where N_{TG-51} is from PPC40 as a reference chamber from cross-calibration. The lowest absorbed dose is at 15 MeV measured by PPC40 (FC65-G as the reference chamber in cross-calibration).

Table 4. Results of calibration correction factors derived from sequential cross-calibration following TRS-398 and TG-51 compared to their calibration correction factors calibrated at country SSDL.

Reference chamber	Field chamber	$N_{TRS-398}$ (Gy/nC)	$N_{TRS-398}/N_{Co}$	Discrepancy (%)	N_{TG-51} (Gy/nC)	N_{TG-51}/N_{Co}	Discrepancy (%)
FC65-G	CC13	0.27392	0.993	-0.68	0.27365	0.992	-0.78
	PPC40	0.08779	0.996	-0.40	0.08725	0.990	-1.01
CC13	FC65-G	0.04866	1.007	0.68	0.04871	1.008	0.79
	PPC40	0.08839	1.003	0.28	0.08794	0.998	-0.23
PPC40	FC65-G	0.04853	1.004	0.40	0.04929	1.020	1.99
	CC13	0.27503	0.997	-0.28	0.27633	1.002	0.19

Note: Discrepancy (%) = 100 × (N_{method} – N_{Co})/(N_{Co})

Table 5. Absorbed dose outcomes of maximum depth dose (at z_{max}) for modified calibration.

Reference chamber	Field chamber	Energy (MeV)	$Modified_{N_{TRS-398}}$		$Modified_{N_{TG-51}}$	
			D_w (cGy/MU)	Discrepancy (%)	D_w (cGy/MU)	Discrepancy (%)
PPC40	CC13	6	0.996	-0.4	1.001	0.1
		9	0.992	-0.8	0.996	-0.4
		12	0.987	-1.3	0.992	-0.8
		15	0.987	-1.3	0.992	-0.8
		18	0.990	-1.0	0.994	-0.6
	FC65-G	6	0.993	-0.7	1.009	0.9
		9	0.985	-1.5	1.001	0.1
		12	0.977	-2.3	0.993	-0.7
		15	0.977	-2.3	0.993	-0.7
		18	0.990	-1.0	1.006	0.6
FC65-G	CC13	6	0.992	-0.8	0.991	-0.9
		9	0.988	-1.2	0.987	-1.3
		12	0.983	-1.7	0.982	-1.8
		15	0.983	-1.7	0.982	-1.8
		18	0.986	-1.4	0.985	-1.5
	PPC40	6	0.995	-0.5	0.989	-1.1
		9	0.992	-0.8	0.986	-1.4
		12	0.987	-1.3	0.981	-1.9
		15	0.986	-1.4	0.980	-2.0
		18	0.998	-0.2	0.992	-0.8
CC13	FC65-G	6	0.996	-0.4	0.997	-0.3
		9	0.988	-1.2	0.989	-1.1
		12	0.980	-2.0	0.981	-1.9
		15	0.980	-2.0	0.981	-1.9
		18	0.993	-0.7	0.994	-0.6
	PPC40	6	1.002	0.2	0.997	-0.3
		9	0.999	-0.1	0.993	-0.7
		12	0.994	-0.6	0.989	-1.1
		15	0.993	-0.7	0.988	-1.2
		18	1.005	0.5	1.000	0.0

Results of average absorbed dose for TRS-398, TG-51, and modified calibration

TRS-398[2] specifies that the beam quality conversion factor (k_{Q,Q_0}) is obtainable exclusively with energies higher than 10 MeV for cylindrical chambers FC65-G and CC13. The half-value depth, R_{50}, determines the beam quality conversion factors, for linear accelerators. According to TG-51[3], cylindrical chambers are recommended for electron beams exceeding 6 MeV. These electron quality conversion factors referred to as $k'_{R_{50}}$, are derived from R_{50} using specific formulas and parameters from TG-51.

Figure 2 shows this study's main results, the average dose per monitor unit (D/MU) at z_{max} for TRS-398, TG-51, and modified formalism. TRS-398 and TG-51 were applied with calibration correction factors from the country SSDL. The average dose was calculated from the three-chamber results. Modified calculation was applied with calibration correction factors derived from TRS-398 and TG-51 protocols cross-calibration based. The average dose was calculated from the results from the three field chambers and their calibration correction factors from cross-calibration based on TRS-398 and TG-51. The error bars depict the standard deviations of the measurement outcomes gathered from all ion chambers for each energy, indicating the variation across all ion chambers and demonstrating the consistency of the results.

The average of absorbed-dose-to-water results from the modified calibration approach closely match those received from TRS-398 and TG-51 methods. The average dose ranged from 0.990-1.000 cGy/MU for TRS-398 and 0.986-0.998 cGy/MU for TG-51. For 6 MeV and 9 MeV absorbed dose measurements under TRS-398, data from parallel-plate chambers were exclusively considered. TRS-398 is the only method that had an average absorbed dose of up to 1.000 cGy/MU which was at 6 MeV, while the lowest average dose per MU is 0.990 at 15 MeV. For modified calibration using $N_{TRS-398}$, the average absorbed doses were between 0.984 and 0.996 cGy/MU while using N_{TG-51} has an average absorbed dose ranging from 0.986-0.997 cGy/MU. Overall, along with energies, absorbed doses of modified calibration have similar trends to TRS-398 and TG-51. However, they started slightly lower than TRS-398 and TG-51 but ended up somewhat higher than TG-51 at 18 MeV.

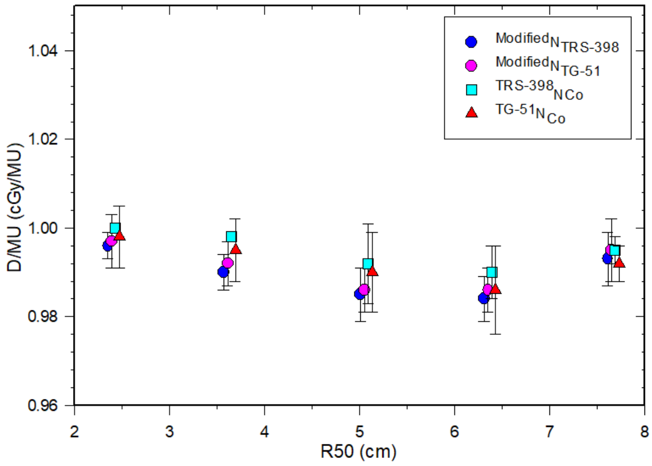

Figure 2. D/MU average absorbed dose to water for all three methods. The plotted points were slightly shifted along the horizontal axis for transparency.

Discussions

Calibration correction factor from cross-calibration

The results of our study, presented in **Table 4**, demonstrate a high degree of precision in calibration correction factors for an 18 MeV electron beam using FC65-G, CC13, and PPC40 ionization chambers. With the correction factor ratios ranging narrowly from 0.990 to 1.020, our findings strongly agree with the standards set by the country SSDL. The maximum percentage difference observed of less than ±2% is particularly noteworthy which underscores the reliability of our study on the modified calibration method. This level of precision is significant for clinical dosimetry, as it may contribute to more accurate dose delivery. Despite these promising results, it is essential to consider the limited scope of beam energy and chamber types used in the cross-calibration study.

Absorbed dose to water for modified electron beam calibration

The results indicate that the modified electron beam calibration, which employed calibration correction factors derived from cross-calibration based on TRS-398 and TG-51 formalism, is effective and yields consistent dose measurements. The absorbed dose per MU, as demonstrated by the findings, shows that these modified methods produce results that are in close alignment with the standard dose unit of 1 cGy/MU, with discrepancies within a clinically acceptable range.

The dose variations using $N_{TRS-398}$ at 12 and 15 MeV, which showed the greatest deviation, suggests that while the method is robust, particular attention may be paid to these energy levels during clinical application. Notably, the lowest absorbed dose measured at 0.977 cGy/MU with the FC65-G (PPC40 as reference chamber) indicates that the modified calibration can result in a conservative dose estimate, beneficial for patient safety. Similarly, the N_{TG-51} calibration's dose measurements across all studied depths offer further confirmation of the method's reliability, with discrepancies from -2.0% to 0.9%. The fact that the greatest positive discrepancy occurred at 6 MeV, while the lowest was at 15 MeV, suggests that energy-dependent factors may influence calibration precision and should be accounted for.

The results demonstrate the efficacy of the modified calibration methods in determining the absorbed dose to water, exhibiting a remarkable agreement with the well-established TRS-398 and TG-51 protocols. The absorbed-dose-to-water ratios, delineated in **Table 6**, reveal that the ratios of $modified_{N_{TRS-398}}$ to $TRS-398_{N_{Co}}$ span a range of 0.982 to 1.010 across the various ionization chambers and energies investigated. Notably, the CC13 (FC65-G as reference chamber) at 12 MeV exhibited a discernible underestimation of -1.8%, while the PPC40 (CC13 as reference chamber) at 18 MeV displayed a 1.0% overestimation.

A parallel analysis of the dose ratios for $modified_{N_{TG-51}}$ relative to $TG-51_{N_{Co}}$ unveiled discrepancies ranging from an underestimation of -1.5% to an overestimation of 2.1%. The most pronounced overestimation of 2.1% was observed with the FC65-G (PPC40 as reference chamber) at an energy of 15 MeV.

While the majority of the deviations from unity remain well within the clinically acceptable range, the overestimation of 2.1% warrants further investigation and potential refinement of the modified calibration approach. However, the observed discrepancies, albeit minor in most cases, underscore the importance of rigorous calibration procedures and meticulous quality assurance measures to guarantee the utmost accuracy in dose delivery.

Table 6. Dose ratios of modified formalism compared to TRS-398 and TG-51 protocols of this study.

Reference chamber	Field chamber	Energy (MeV)	$\frac{Modified_{N_{TRS-398}}}{TRS-398_{N_{Co}}}$	Discrepancy (%)	$\frac{Modified_{N_{TG-51}}}{TG-51_{N_{Co}}}$	Discrepancy (%)
PPC40	CC13	6	—	—	0.996	-0.4
		9	—	—	0.995	-0.5
		12	0.986	-1.4	0.995	-0.5
		15	0.991	-0.9	0.999	-0.1
		18	0.992	-0.8	1.001	0.1
	FC65-G	6	—	—	1.020	2.0
		9	—	—	1.015	1.5
		12	0.997	-0.3	1.016	1.6
		15	0.996	-0.4	**1.021**	**2.1**
		18	0.999	-0.1	1.020	2.0
FC65-G	CC13	6	—	—	0.987	-1.3
		9	—	—	**0.985**	**-1.5**
		12	**0.982**	**-1.8**	**0.985**	**-1.5**
		15	0.987	-1.3	0.989	-1.1
		18	0.988	-1.2	0.991	-0.9
	PPC40	6	0.995	-0.5	0.988	-1.2
		9	0.994	-0.6	0.987	-1.3
		12	0.992	-0.8	0.986	-1.4
		15	0.994	-0.6	0.987	-1.3
		18	1.003	0.3	0.996	-0.4
CC13	FC65-G	6	—	—	1.008	0.8
		9	—	—	1.003	0.3
		12	1.000	0.0	1.004	0.4
		15	0.999	-0.1	1.009	0.9
		18	1.002	0.2	1.008	0.8
	PPC40	6	1.002	0.2	0.996	-0.4
		9	1.001	0.1	0.995	-0.5
		12	0.999	-0.1	0.994	-0.6
		15	1.001	0.1	0.995	-0.5
		18	**1.010**	**1.0**	1.004	0.4

Note: $Discrepancy\ (\%) = 100 \times (Modified_{N_{TRS-398}} - TRS-398_{N_{Co}}) / TRS-398_{N_{Co}}$
$Discrepancy\ (\%) = 100 \times (Modified_{N_{TG-51}} - TG-51_{N_{Co}}) / TG-51_{N_{Co}}$

Average absorbed dose for TRS-398, TG-51, and modified formalism

The absorbed dose per MU with all chambers for modified calibration was determined by using calibration correction factors from cross-calibration based on the two protocols, as opposed to the absorbed dose per MU for TRS-398 and TG-51 with calibration correction factors from country SSDL. **Figure 2** presents the study's results, which show that all average absorbed doses for all methods ranging from energy 6 to 18 MeV are within the tolerance (±2%) of the clinical standard dose per MU.

Figure 3 compares the results of this study's average absorbed dose of different chambers in prior research. This study's absorbed dose to water revealed values that aligned with earlier published research. The result from Muir (2020)[6] using 4 cylindrical chambers (NE2571, 30013, CC13, and A1SL) and 2 parallel-plate chambers (NACP-02 and Roos) with Elekta Precise showed -0.2% to 0.6% difference in D/MU for modified methods; Pawiro et al. (2022) [8] using four ion chambers (PTW 30013, IBA CC13, Exradin A1S1, and Exradin A11) with Elekta linac Synergy platform, the discrepancy compared to the standard dose unit ranged from -0.2% to 0.8% while using Elekta versa HD the deviation was -1.3% to -0.2%. In 2023, Yulinar et al.[9] studied 3 chambers (IBA-CC13, Exradin-A1S1, and Exradin-A11) and showed that for Synergy Platform, the deviation of average absorbed dose is -0.2% to 1.0% while Eleka versa HD the deviation was -0.4% to 1.0%. In this investigation, the difference compared to the standard dose for the modified calibration was between -1.6% and -0.4% when applying $N_{TRS-398}$ but when we applied N_{TG-51} to modified calibration, the difference in the average absorbed dose was between -1.4% and -0.3%. These deviations were a bit small compared with those earlier published papers because different chambers and calibration correction factor sources were used and methods of deriving calibration correction factors to use in absorbed dose-to-water calculation.

The ratio of the average absorbed dose of modified calibration compared to TRS-398 and TG-51 of this study and previous studies are presented in **Figure 4** and **Figure 5**. Pawiro et al.[8] studied with the energies 6-15 MeV. With Synergy Platform, the average dose ratio of modified calibration to TRS-398 ranged from 1.004 to 1.013. With Versa HD, the average dose ratio of modified calibration in comparison to TRS-398 is 1.003 to 1.013. The average absorbed dose for modified calibration is higher than TRS-398 by about 0.3% to 1.3%. Yulinar et al.[9] studied the same two linac machines and energies, but the depths in the water phantom were slightly different. The results of the average dose ratio between modified calibration and TRS-398 for Elekta Synergy Platform is 1.005-1.021 while with Eleka Versa HD the comparison shows that 0.992-1.010. In this study, when modified calibration was applied with $N_{TRS-398}$, the average dose ratio compared to TRS-398 was 0.993-0.999. Overall, the average dose ratio of this study is lower than the previous studies, and it is close to the current protocol-TRS-398.

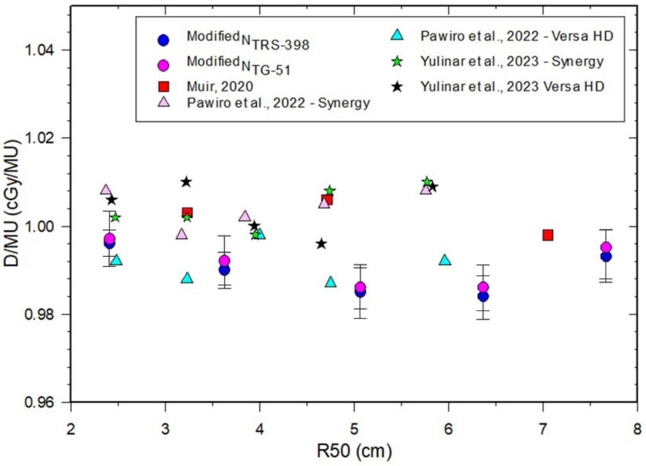

Figure 3. Average absorbed dose to water for modified calibration using $N_{TRS-398}$ and N_{TG-51} compared to previous studies.

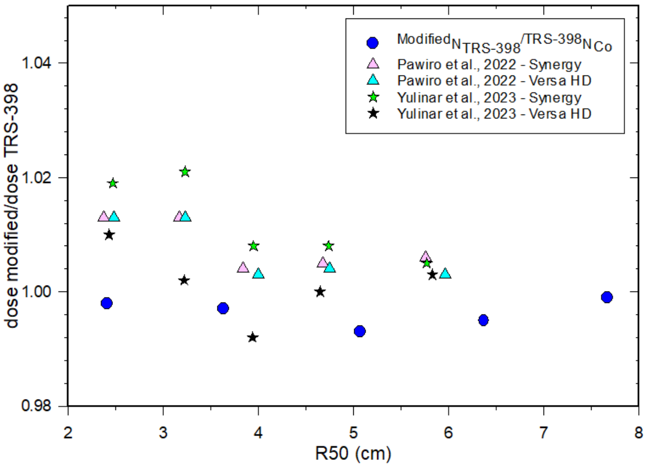

Figure 4. Average absorbed-dose-to-water ratios between modified calibration and TRS-398 compared to previous studies.

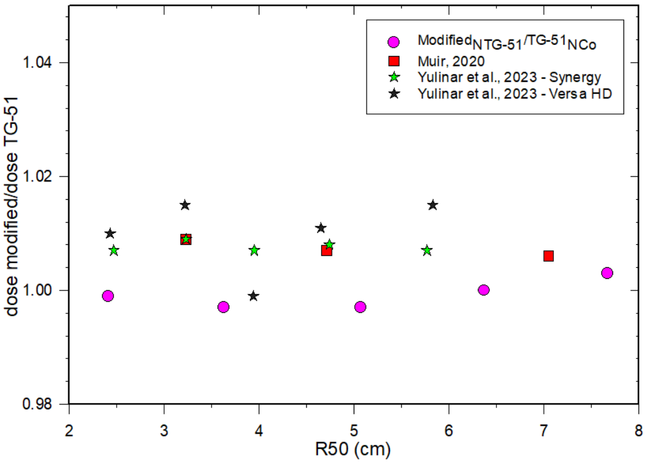

Figure 5. Average absorbed-dose-to-water ratios between modified calibration and TG-51 compared to previous studies.

According to Muir[6], the average dose ratio of modified calibration to TG-51 ranges from 1.006-1.009. The average absorbed dose for the modified method is higher than TRS-398 by about 0.6% to 0.9%. Yulinar et al.[9] studied the same two linac machines and energies. The results of the average dose ratio between modified calibration and TG-51 for Elekta Synergy Platform are 1.007-1.009 while with Eleka Versa HD the comparison shows that 0.999-1.015. In this study, when modified formalism was applied with N_{TG-51}, the average dose ratio compared to TRS-398 was 0.997-1.003. Overall, the average dose ratio of this study is close to the current protocol-TG-51.

Conclusions

This study validated the effectiveness of modified electron beam calibration methods by conducting a detailed analysis against the established IAEA TRS-398 and AAPM TG-51 protocols by using calibration correction factors from cross-calibration based on the two mentioned protocols. Utilizing cylindrical (FC65-G and CC13) and parallel-plate (PPC40) ionization chambers, the modified methods demonstrated consistent adherence to accepted standards, with absorbed dose values to water ranging from 0.977-1.005 cGy/MU and 0.980-1.009 cGy/MU by using $N_{TRS-398}$ and N_{TG-51}, respectively. Dose ratios compared to TRS-398 varied between 0.982-1.010, and TG-51 was between 0.985-1.021. Overall, its average absorbed dose to water using $N_{TRS-398}$ and N_{TG-51} ranged from 0.984-0.996 cGy/MU and 0.986-0.997 cGy/MU, respectively, confirming that all values were well within the IAEA's ±2% tolerance threshold.

The importance of cross-calibration, as reinforced by TRS-398 and TG-51, is highlighted by its role in ensuring the accuracy and reliability of modified calibration methods. These findings suggest that the modified approaches can provide an effective alternative to traditional protocols, potentially enhancing dosimetric precision and flexibility in clinical settings. This approach will ensure the integrity of dosimetry in therapeutic radiation, contributing to the safety and effectiveness of patient treatments in radiotherapy.

Acknowledgments

We gratefully acknowledge the support from the UI GREAT Scholarship from Universitas Indonesia for this research. This study is also partially funded by PUTI research grant Universitas Indonesia with contract number NKB-291/UN2.RST/HKP.05.00/2022

References

1. Elbashir FEM, Ksouri W, Eisa MH, et al. Comparison of dosimetry protocols for electron beam radiotherapy calibrations and measurement uncertainties. Life. 2022;12(1):1-11. doi:10.3390/life12010031
2. Andreo P, Radiation M, Section P. Technical Reports Series No. 398, Absorbed Dose Determination in External Beam Radiotherapy (Vienna: International Atomic Energy Agency). Atomic Energy. 2006;12:183.
3. Almond PR, Biggs PJ, Coursey BM, et al. AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. Med Phys. 1999;26(9):1847-1870. doi:10.1118/1.598691
4. Wittkamper FW, Thierens H, Van Der Plaetsen A, De Wagter C, Mijnheer BJ. Perturbation correction factors for some ionization chambers commonly applied in electron beams. Phys Med Biol. 1991;36(12):1639-1652. doi:10.1088/0031-9155/36/12/008
5. Muir BR, McEwen MR. Technical Note: On the use of cylindrical ionization chambers for electron beam reference dosimetry: On. Med Phys. 2017;44(12):6641-6646. doi:10.1002/mp.12582
6. Muir BR. A modified formalism for electron beam reference dosimetry to improve the accuracy of linac output calibration. Med Phys. 2020;47(5):2267-2276. doi:10.1002/mp.14048
7. Van der Plaetsen A, Seuntjens J, Thierens H, Vynckier S. Verification of absorbed doses determined with thimble and parallel-plateionization chambers in clinical electron beams using ferrous sulphate dosimetry. Med Phys. 1994;21(1):37-44. doi:10.1118/1.597362
8. Pawiro SA, Mahfirotin DA, Assegab MI, Wibowo WE. Modified electron beam output calibration based on IAEA Technical Report Series 398. J Appl Clin Med Phys. 2022;23(4):1-9. doi:10.1002/acm2.13573
9. Yulinar C, Assegab MI, Wibowo WE, Pawiro SA. Modified calibration protocols in electron beam dosimetry: comparison with IAEA TRS-398 and AAPM TG-51. Biomed Phys Eng Express. 2023;9(5). doi:10.1088/2057-1976/ace722
10. Dwi Aprilia Mahfirotin, Brian Ferliano, Andrian Dede Handika, Yosi Sudarsi Asril, Muhamad Fadli, Dea Ryangga, Nelly Nelly, Eddy Kurniawan, Wahyu Edy Wibowo, Poonam Yadav SAP. A multicenter study of modified electron beam output calibration. J Appl Clin Med Phys. 2024;25(1):1-10. doi:10.1002/acm2.14232
11. Muir BR, Rogers DWO. Monte Carlo calculations of electron beam quality conversion factors for several ion chamber types. Med Phys. 2014;41(11). doi:10.1118/1.4893915
12. IAEA TRS 398. Absorbed Dose Determination in External Beam Radiotherapy. Atomic Energy. Published online 2000:1-229.