



Article Analysis of Uncertainties in Clinical High-Energy Photon Beam Calibrations Using Absorbed Dose Standards

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Abstract: We compared the results of absorbed dose measurements made using the TRS-398, TG-51, and DIN protocols and their associated uncertainties to reduce discrepancies in measurement results made using the three protocols. This experiment was carried out on two Varian Medical linear accelerators with 4, 6, 10, and 20 MV photon energies using FC65-G and CC15 (cylindrical) and NACP-02-type (plane-parallel) ion chambers in water phantoms. The radiation beam quality index (Q) was determined from the measurement of percentage depth dose. It was used to determine the photon beam quality factor required with the ionization chamber calibration factor to convert the ion chamber reading into the absorbed dose to water. For the same beam quality, the TRS-398/TG-51 varied from 0.01% to 1.8%, whereas the ratio for TRS-398/DIN 6800-2 varied from 0.1% to 0.88%. The chamber-to-chamber variation was 0.09% in TRS-398/TG-51, 0.03% in TRS-398/DIN, and 0.02% in TG-51/DIN 6800-2. The expanded uncertainties (k = 1) were 1.24 and 1.25 when using TRS-398 and DIN 6800-2, respectively. Using the aforementioned three protocols, the results showed little chamber-to-chamber variation and uncertainty in absorbed dose measurements. The estimated uncertainties when using cylindrical ion chambers were slightly lower than those measured using plane-parallel chambers. The results are important in facilitating comparisons of absorbed dose measurements when using the three protocols.

Keywords: radiotherapy; radiation dosimetry; ionization chamber; Linac; absorbed dose to water; dosimetry protocols

1. Introduction

Current protocols for calibrations of external beam radiotherapy are based on absorbed standards. These include the AAPM TG51 protocol implemented in North America, the DIN 6800-2 protocol in German-speaking countries and the Institute of Physics Code of Practice, the IPEM 1996 protocol in the UK, and NCS Report No. 18 in the Netherlands. Conversely, IAEA TRS-398, the international atomic energy dosimetry protocol, is used internationally [1–5].

The benefits of having a protocol based on absorbed standards, which include reduced uncertainty, establish a harmonized system of primary standards, coupled with the use of a simple, straightforward formalism [2,3]. Achieving accuracy in radiotherapy necessitates dose standardization, which reduces measurement discrepancies and ensures traceability. For these reasons, comparing dosimetry protocols increases traction in research, which has



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). been discussed extensively in the literature [6–9]. There is always a need to report progress in dosimetry practices and compare uncertainties in absorbed dose measurements using commonly used protocols and codes of practices.

Herein, we compared absorbed dose to water measured using the IAEA 398, DIN 6800-2, and TG-51 protocols in a concert of a plane-parallel and two cylindrical chambers to determine dose conversion coefficients between the three most common dosimetry protocols. Chamber-to-chamber variations and their influence in absorbed dose measurements were also investigated. The results were anticipated to facilitate the intercomparison of measurements performed using the three-dosimetry protocols.

The three protocols' common feature is that they are all based on absorbed dose standards where the calibrated ionization chambers have absorbed dose to water calibration factors. However, the three protocols differ in defining the beam quality index used to determine the beam quality conversion coefficients required to convert the ionization chamber reading into absorbed dose to water. Also, there are some differences in the methods used to determine correction factors for influence quantities that affect ionization chamber readings. Our results reflected the influence of these differences on absorbed dose measurements.

Herein, we aimed to compare the absorbed dose measurements made using three comprehensive dosimetry protocols and their associated uncertainties. The results may help in understanding discrepancies in measurement results made using the three protocols.

1.1. Dosimetry Formalism

According to TRS-398, absorbed dose to water (D_w) at a reference beam quality can be determined using Equation (1):

$$D_{w,Q} = M_Q N_{D,w,Q_o} k_{Q,Q_o} \tag{1}$$

where N_{D,w,Q_o} is the absorbed dose to water calibration factor and k_{Q,Q_o} is the beam quality correction factor that accounts for the differences between beam quality Q_o (from a reference calibration laboratory) and beam quality Q (from a user hospital). Field measurements were performed at a user hospital. M_Q refers to corrected hospital measurements. The uncorrected hospital measurements, M_{raw} , are corrected using Equation (2):

$$M_Q = M_{raw} k_{TP} K_{elec} k_{pol} k_s \tag{2}$$

Here, k_{TP} corrects for the nonreference ambient temperature and pressure during hospital measurements. Moreover, K_{elec} is the electrometer calibration factor, k_{pol} is the polarity correction factor, and k_s is the ion recombination correction factor. Using the TG-51 protocol, $D_{w,Q}$, at reference depth dref, is determined using Equation (3):

$$D_w^Q = Mk_Q D_{D,w}^{60Co} \tag{3}$$

Here, M refers to corrected hospital measurements and k_Q is the beam correction factor that translates N_{D,w,Q_0} for a ⁶⁰Co beam into $N_{D,w,Q}$ for the user beam quality Q. As in the German protocol DIN 6800-2 [5], the absorbed dose to water, Dw (P_{eff}), is determined using Equation (4):

$$D_{\rm w}(P_{\rm eff}) = kNM \tag{4}$$

Here, k is the product of all factors that account for the nonreference influence quantities that affect the measurement results. The effective point of measurement (P_{eff}) approach shifts the chamber axis toward the radiation source by approximately 0.5 r_{cyl} (radius of a cylindrical chamber).

1.2. Correction Factors for Influence Quantities

The correction factor for the nonreference temperature and pressure k is obtained by:

$$k_{TP} = \frac{(273.15+T)P_o}{(273.15+T_o)P}$$
(5)

Here, *P* and *T* are the measured air pressure and temperature, respectively, and *P*_o and *T*_o are the reference values (101.13 kPa and 20 °C) used in this study.

The ion recombination factor ks accounts for incomplete charge collection due to ion recombination in the gas cavity. In the IAEA TRS-398 and AAPM TG-51 dosimetry protocols, ks is determined using a two-voltage technique. Here, k_s at the normal operating voltage V1 is provided by [1,2,5]:

$$k_{s} = a_{o} + a_{1} \left(\frac{M_{1}}{M_{2}}\right) + a_{2} \left(\frac{M_{1}}{M_{2}}\right)^{2}$$
(6)

Here, *M*1 and *M*2 are the collected charges that correspond to the voltages V1 and V1, respectively, provided that the ratio V1/V2 > 3 and a are coefficients used to determine k_s .

Using an ionization chamber with polarity opposite to the one used during calibration at the reference laboratory can affect chamber readings. These can be corrected for using the polarity correction factor k_{pol} , determined by [1,2,5]:

$$k_{pol} = \left(\frac{|M_+| + |M_\pm|}{2M}\right) \tag{7}$$

Here, M+ and M- are the measurements obtained at positive and negative polarity, respectively, and M is the measurement obtained with the commonly used polarity.

2. Materials and Methods

Experimental measurements for following the IAEA 398, TG-51, and DIN 6800-2 dosimetry protocols were collected using two Varian Medical linear accelerators, the Linac 2300 C and Linac 2100 C, with nominal photon beam qualities of 4, 6, 10, and 20 MV (Varian, Palo Alto, CA, USA). The linear accelerator beams had a repletion rate of 50 Hz, and we used a pulse frequency of 200 MU/min for all beams. Experimental measurements were carried out according to standard conditions recommended for each protocol.

2.1. Dosimetry Equipment

The chambers used in this study were as follows: a Scanditronix Wellhofer FC65-G cylindrical chamber (SN 1630) with a cavity volume of 0.6 cc, featuring a graphite wall and an Al central electrode; a Scanditronix Wellhofer CC15 cylindrical chamber (SN 3560) with a cavity volume of 0.3 cc, featuring a PMMA wall with graphite coating and an Al central electrode; and a Scanditronix Wellhofer NACP-02 plane-parallel-type chamber with 0.7 mm entrance window made of Mylar foil (SN 13505). Ionization chambers used in this study were calibrated at the IBA standard laboratory, with their calibrations traceable to the German reference laboratory (PTB). As recommended, we cross-calibrated the plane-parallel chambers against the FC65-G reference cylindrical chamber in each of the photon beams under study [1,2,5]. All doses were measured using a Wellhofer computerized water phantom (IBA Dosimetry, Schwarzenbruck, Germany).

The percentage depth dose (*PDD*) is the absorbed dose measured at depth d, and on the central axis to that, measured at reference point d_{max} for a certain field size at the phantom surface at 100 cm SSD [10–12]. The *PDD* measurements were performed using FC65-G reference ionization chamber mounted on a Wellhofer computerized water phantom (IBA Dosimetry).

2.2. Determination of the Beam Quality Specifiers

The IAEA TRS-398 and DIN 6800-2 protocols use the tissue–phantom ratio, $TPR_{20,10}$. It is defined as the percentage of absorbed dose measured on the beam axis at depths of 20 and 10 cm in a water phantom at a constant source–detector distance (SDD) of 1 m and a field size of 10 × 10 cm [1,2,4]. $TPR_{20,10}$ describes the approximate exponential decrease of a photon beam at a depth of the maximum dose, excluding electron contamination [13]. $TPR_{20,10}$ values were determined from direct measurements as well as estimated from the *PDD* using Equation (8) [2,4]:

$$TPR_{20,10} = 1.2661.PDD_{20,10} - 0.0595 \tag{8}$$

Here, $PDD_{20,10}$ is the percentage depth dose at 10 to 20 cm in water for a standard field size of 10 × 10 cm at an SSD of 100 cm. AAPM TG-51 uses %*dd* (10)*x* as a beam quality index, defined as the *PDD* at 10 cm depth in water, due to photon-only exclusion of electron contamination [1]. At beam energies below 10 MV, %*dd* (10)*x* = %*dd* (10). For beam energies \geq 10 MV, %*dd* (10)Pb was measured with a 1 mm lead foil placed to interrupt the beam at 30 cm from the phantom and determined using Equation (9):

$$2\% dd (10)_{\gamma} = [0.8116 + 0.00264\% dd (10)_{Ph}]\% dd (10)_{Ph}$$
(9)

The *PDD* was measured using an FC65-G chamber mounted on a Wellhofer computerized water phantom. Photon beam quality conversion coefficient (K_Q) values for the ionization chambers of interest in radiotherapy are available in a lookup table as a function of %*dd* (10)*x* in AAPM TG-51 and as a function of *TPR*_{20,10} in IAEA TRS-398. On the contrary, the beam quality conversion factors for the plane-parallel chambers were determined using calibration coefficients for the user beam (Q) and the reference beam (Q_0) qualities according to the method described by Hohlfeld [14].

$$k_{Q,Q_o} = \frac{N_{D,w}^Q}{N_{D,w}^{Q_o}}$$
(10)

2.3. Absorbed Dose Measurements

An absorbed dose to water measurement involves using an ionization chamber with absorbed dose to water calibration factor in water phantom according to the reference conditions recommended in TRS-398, TG-51, and DIN 6800-2 dosimetry protocols. This includes determining the radiation beam quality index (Q) to determine the photon beam quality factor required along with the ionization chamber calibration factor to convert the ion chamber reading into the absorbed dose to water, according to Equations 1, 3, and 4 [1,2,5].

For absorbed dose to water measurements, the cylindrical chamber was placed with its axis at reference depth of measurements in water phantom (Z_{ref}), which equaled 5 cm (for 4 and 6 MV) and 10 cm (for 10 and 20 MV) in all protocols. Measurements were taken at the chamber reference point of measurements, which is at the chamber axis at the center of the cavity volume in IAEA TRS-398 and AAPM TG-51. In DIN 6800-2, measurements are taken at the effective point of measurement (Peff) shifted toward the radiation source by approximately 0.5 r_{cyl}. For a parallel-plate chamber, the reference point of measurements is located at its center on the inner surface of the front window.

Using the *PDD*, all doses were then converted to doses at a depth of the dose maximum d_{max} .

$$D_{w,Q}(d_{max}) = 100 \cdot D_{w,Q} \left(Z_{ref.} \right) / PDD \left(Z_{ref} \right)$$
(11)

2.4. Measurement Uncertainty

The term uncertainty is defined as a parameter that characterizes the dispersion of values obtained for a particular measurement when performed repeatedly. To maintain

the required accuracy in radiotherapy, the increase in toxicity needs to be limited to 3%, for which dose uncertainties (σ D) need to be kept <5% [15]. The combined uncertainties in the absorbed dose to water can be calculated using error propagation from the relevant standard uncertainties [16]. The combined uncertainty in the absorbed quantity to water, calculated according to IAEA TRS-398 (Equation (1)), can be expressed as:

$$\frac{u(D_{w,Q})}{D_{w,Q}} = \sqrt{\left(\frac{u(M_Q)}{M_Q}\right)^2 + \left(\frac{u(N_{D,w,Q_o})}{N_{D,w,Q_o}}\right)^2 + \left(\frac{u(k_{Q,Q_o})}{k_{Q,Q_o}}\right)^2}$$
(12)

where $u(M_Q)$, $u(N_{D,w,Q_o})$, and $u(k_{Q,Q_o})$ are the standard uncertainties in the corrected hospital measurement, absorbed dose to water calibration factor, and beam quality correction factors, respectively. The ratio of the standard uncertainty to the evaluated quantity is named the relative uncertainty as shown in Equation (12). The term $u(M_Q)$ in Equation (12) can be written as:

$$\frac{\mathbf{u}(M_Q)}{M_Q} = \sqrt{\left(\frac{\mathbf{u}(M_{raw})}{M_{raw}}\right)^2 + \left(\frac{\mathbf{u}(k_{TP})}{k_{TP}}\right)^2 + \left(\frac{\mathbf{u}(K_{elec})}{K_{elec}}\right)^2 + \left(\frac{\mathbf{u}(k_{pol})}{k_{pol}}\right)^2 + \left(\frac{\mathbf{u}(k_s)}{k_s}\right)^2}$$
(13)

where $u(M_{raw})$, $u(k_{TP})$, $u(K_{elec})$, $u(k_{pol})$, and $u(k_s)$ are the standard uncertainties for uncorrected chamber readings, temperature and pressure, electrometer calibration, polarity, and ion recombination, respectively. These standard uncertainties constituted type A uncertainties evaluated using statistical methods and B uncertainties evaluated using methods other than the statistical methods. The combined uncertainty in N_{D,W}, calculated according to AAPM TG-51 and DIN 6800-2, had a similar expression as Equation (11). The measurement results' overall uncertainties were quoted as expanded uncertainty at 68% confidence level with coverage factor (k = 1) [16].

3. Results

Figure 1 shows the percentage depth dose (*PDD*) curves from 4, 6, 10, and 20 MV photon beams in a 10×10 cm field. Table 1 presents the characteristics of the percentage depth dose curves.



Figure 1. The percentage depth doses from 4, 6, 10, and 20 MV photon beams in a 10×10 cm field.

IAEA TRS-398	4 MV	6 MV	10 MV	20 MV
R100 (mm)	11.10	13.20	23.20	33.00
D100 (%)	62.60	67.09	73.34	80.90
D200 (%)	33.58	38.85	46.39	54.50
TPR 20/10	0.628	0.677	0.745	0.797

Table 1. Characteristics of percentage depth dose curves for 4, 6, 10, and 20 MV photon beams.

Table 2 presents the main dosimetry parameters for the photon beams studied: $S_{w,air}$, $TPR_{20,10}$, and %*dd* (10)*x*. The k_{Q,Q_0} values for the ion chambers used in this study are presented in Table 3. $TPR_{20,10}$ estimation from a *PDD* is less accurate than a direct measurement. Therefore, in this study, we used $TPR_{20,10}$ values obtained from direct measurements.

Table 2. The main dosimetry parameters for the photon beams studied, including: $S_{w,air}$, $TPR_{20,10}$, and % dd (10)x.

MV	TPR ₂	20,10	0/ 11/(10)	S _{w,air}	
	Measurements	From PDD	% aa (10)x.		
4	0.619	0.628	62.66	1.127	
6	0.675	0.677	67.27	1.119	
10	0.738	0.745	72.60	1.106	
20	0.793	0.797	82.50	1.084	

kQ **Beam Energy** Chamber (MV) **TRS-398** TG-51 DIN 6800-2 4 0.9991 1.0003 0.996 10 0.9665 0.9633 0.9607 NACP-02 0.9960 6 0.9991 1.0032 20 0.9607 0.9665 0.9633 4 0.9981 0.9996 0.9991 10 0.9815 0.9854 0.9836 CC15 6 0.9953 0.9913 0.9933 20 0.9981 0.9656 0.9622 4 0.9981 0.9991 0.9971 10 0.9854 0.9815 0.9914 FC65-G 6 0.9953 0.9913 0.9925 20 0.9685 0.9656 0.9638

Table 3. $k_{Q,Q0}$ values for the ion chambers used in this study.

Table 4 presents the k_{pol} , ks, and k_{TP} correction factors. A maximum variability of 0.2% was found in the kpol values using the DIN 6800-2 protocol, while the variability was 0.38% using TRS-398.

Table 5 presents the absorbed dose conversion factors of TRS-398, TG-51, and DIN 6800-2. Excluding the FC65-G reading at 6 MV, the absorbed dose ratios TRS-398/TG-51, TRS-398/DIN 6800-2, and TG-51/DIN 6800-2 varied from 0.01% to 1.04%, 0.1% to 0.88%, and 0.1% to 0.7%, respectively.

Chamban		6 MV			20 MV			4 MV			10 MV	
Chamber	TRS	TG-51	DIN									
k _{nol}												
NACP	0.9981	0.9981	0.9982	0.999	0.999	0.999	0.999	0.9971	0.999	0.9978	0.9978	0.9978
CC15	0.9994	0.9995	0.9994	0.9994	0.9995	0.9994	0.9988	1.0002	0.9988	0.9998	0.9998	0.9998
FC65-G	0.9989	0.9987	0.9989	0.9989	0.9989	0.9989	0.9989	0.9987	0.9989	0.9989	0.9989	0.9989
						ks						
NACP	1.0062	1.0062	1.0033	1.0071	1.0073	1.0045	1.0036	1.0032	1.0028	1.0026	1.0027	1.0023
CC15	1.0043	1.0043	1.0031	1.0043	1.0043	1.0031	1.0026	1.0017	1.0023	1.0027	1.0028	1.0023
FC65-G	1.0025	1.0027	1.0022	1.0033	1.0035	1.0027	1.0025	1.0027	1.0022	1.0033	1.0035	1.0027
k_{TP}												
NACP	1.0041	1.0041	0.9973	1.0041	0.9973	1.0041	1.0127	1.0058	1.0127	1.0127	1.0058	1.0127
CC15	1.0135	1.0066	1.0135	1.0135	1.0066	1.0135	1.0128	1.006	1.0128	1.0128	1.006	1.0128
FC65-G	1.0130	1.0061	1.013	1.013	1.0061	1.0130	1.0130	1.0061	1.0130	1.0130	1.0061	1.0130

Table 4. Correction factors for the polarity effect (*kpol*), ion recombination (*ks*), and temperature and pressure correction factors (k_{TP}).

Table 5. Ratios of the absorbed dose to water between the TRS-398, TG-51, and DIN 6800-2 dosimetry protocols using FC65-G, CC15, and NACP-02 ionization chambers.

MV	Ionization Chamber	TRS-398/ TG-51	TRS-398/DIN 6800-2	TG-51/DIN 6800-2
4	FC65-G	0.9999	1.0010	1.0011
	CC15	1.0022	1.0012	0.9990
	NACP-02	1.0021	1.0011	0.9990
6	FC65-G	1.0177	1.0051	0.9935
	CC15	1.0104	1.0033	0.9930
	NACP-02	1.0098	1.0050	0.9952
10	FC65-G	1.0077	1.0039	0.9962
	CC15	1.0086	1.0044	0.9958
	NACP-02	1.0077	1.0047	0.9970
20	FC65-G	1.0103	1.0088	0.9985
	CC15	1.0079	1.0079	1.0000
	NACP-02	1.0096	1.0074	0.9979

4. Discussion

The D_w measurements using the three dosimetry codes of practice showed comparable results. Minor discrepancies in measured absorbed doses arose from the characteristics of the photon beam used, the ionization chamber used, and the measurements of the influence quantities [6]. Two things correct chamber readings: perturbation factors that correct deviations from Bragg–Gray behavior and influence quantities that correct for nonreference conditions, including k_{pol} , ks, and k_{TP} correction factors. Different components of the perturbation factors included in the beam quality correction factors influenced the uncertainties.

Although the two protocols use different beam quality specifiers, the differences in absorbed dose measurements using $TPR_{20,10}$ and %dd (10)x are small—about 0.5% for external beam radiotherapy and $\le 1\%$ for calibrations in primary and other standard laboratories [17]. Thus, the effect of different beam quality indexes is small compared with the overall uncertainties [6,17]. Our results emulated previous studies, which reported discrepancies in absorbed dose measurements among the three protocols that varied from 0.23% to 0.7% [9,17,18]. The results were ascribed to the differences in methods used for beam quality determination and measurements of chamber influence parameters.

Figure 2 presents ratios of the measured D_w obtained with three dosimetry protocols, (a) AAPM TG-51/IAEA TRS-398, (b) IAEA TRS-398/DIN 6800-2, and (c) AAPM TG-51/DIN 6800-2. The obtained chamber-to-chamber variation was 0.09% in TRS-398/TG-51, 0.03% in TRS-398/DIN, and 0.02% in TG-51/DIN 6800-2.





The cylindrical chambers demonstrated a chamber-to-chamber dose variation of 0.09%. The NACP-02 chamber showed a variation of about 1.01% compared with the cylindrical chambers. Cylindrical chambers are recommended for photon beam calibrations, whereas parallel-plate chambers are recommended for photon beam energies ≤ 6 MV. Thus, large uncertainties were expected for the 10 and 20 MV photon beams. Different components of the dosimetry measuring system contribute to some uncertainties, including entrance window and chamber positioning, as demonstrated by Kinoshita et al. [19,20]. Compared with the findings of similar studies, Zakaria, Schuette, and Younan [17] reported deviations of at least 0.23% in D_w measured using the TG-51 and TRS-398 protocols compared with the DIN 6800-2 protocol [2].

Recently, Al-Ahbabi et al. [8] compared D_w values measured using the TRS-398 and TG-51 protocols. Using the TRS-398 protocol, the mean D_w values varied only by 0.13%–0.2% on average compared with TG-51 protocol.

Table 6 shows the relative uncertainties (%) associated with measurements made using the IAEA TRS-398 and DIN 6800-2 protocols. The estimated combined uncertainties for TRS-398 and DIN 6800-2 were 1.24% and 1.25%, respectively. For a particular protocol, the

Cylindrical Chamber **Plane-Parallel Chamber Influence Quantities** Source **Evaluation Type TRS-398** DIN 6800-2 **TRS-398** DIN 6800-2 Chamber certificate В 0.55 0.55 0.55 0.55 $N_{D,W}$ Depth of measurement Calculated В 0.33 0.33 0.33 0.33 Calculated A/B 0.040.04 0.12 0.12 k_{pol} k_{TP} Calculated A/B 0.010.01 0.010.01 k_S Calculated В 0.040.04 0.120.12IAEA TRS-398 В 1 1 k_Q DIN 6800-2 В 1 1 k_E Interaction coefficient IAEA TRS 277 В 0.28 0.28 0.28 0.28Dosimeter stability Dosimeter manual В Dosimeter reading 0.20 0.20 0.20 0.20 Calculated А Combined uncertainty (k = 1)1.24 1.24 1.25 1.25

estimated uncertainties in absorbed dose to water, measured using cylindrical ion chambers are slightly lower than those measured using plane-parallel chambers.

Table 6. Relative uncertainty (%) associated with absorbed dose to water, N_{D,W}, measurements using the IAEA TRS-398 and DIN 6800-2 dosimetry protocols.

As demonstrated in this study, a significant contribution to the overall uncertainty came from the beam quality correction factor, kQ, which amounted to 1.0%, followed by the calibration factor, which amounted to 0.55%. In a similar study, Castrillón and Henríquez [9] compared the IPEM 1990 protocol for photon dosimetry with the IAEA TRS-398 and AAPM TG-51 protocols. The combined uncertainty (k = 1) for the absorbed dose measurements was 1.4 (range: 1.53–1.88), which is comparable to our results. Our findings are thus consistent with the most recent IAEA recommendations, as uncertainties for clinical high-energy photon beams were estimated to be about 1.5% [15].

5. Conclusions

This study compared absorbed dose to water conversion coefficients among the three most common dosimetry protocols—TRS-398, TG-51, and DIN—and showed a high degree of consistency in measurements. Chamber-to-chamber variations in absorbed dose measurements were insignificant, although minor uncertainties in the results were seen when using cylindrical chambers instead of plane-parallel chambers. Estimated uncertainties for cylindrical ion chambers were slightly lower than those measured using plane-parallel chambers. Furthermore, significant uncertainties arose from the beam quality correction factor. We concluded that equipping standard laboratories with medical linear accelerators may reduce uncertainties.

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