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Enhancing Dosimetry Accuracy: Characterization and Verification of an Experimental Cylindrical Graphite Ionization Chamber for Dosimetry of Therapeutic Photon Beams in Reference Conditions

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Abstract

Introduction: Three cylindrical graphite ionization chambers have been constructed, one of which, DW3, participated in the BIPM.RI(I)-K4 key comparisons for absorbed dose to water in a gamma radiation field of the ^{60}Co radionuclide, achieving a positive result. This prompted us to attempt to use the experimental DW2 chamber (twin to DW3 chamber) for dosimetry of high-energy photon beams used clinically with the aim of reducing the value of the total standard uncertainty of the measured radiation dose.

Material and methods: The performance of the DW2 chamber was first tested in gamma ray fields of ^{137}Cs and ^{60}Co. Subsequently, the chamber was calibrated in a ^{60}Co beam relative to the GUM primary standard (DW3). Then, the k_Q factors for 6, 10, and 15 MV photon beams produced by Versa HD, Elekta accelerators were determined using Monte Carlo methods. Next, for the same beams, the correction factors for saturation (k_s) and the polarity (k_{pol}) were experimentally determined. Finally, the DW2 chamber was used to measure the absorbed dose to water under reference conditions. The obtained results were compared to those of a commercial Farmer-type ionization chamber, model 30013 by PTW. A metrological conformity test was used for evaluation.

Results: The relative differences between the two chambers (DW2 vs Farmer chamber) in measured absorbed dose to water for 6, 10, and 15 MV photon beams were -0.1 %, 0.2 %, and 0.7 %, respectively. The relative standard uncertainties of the dose measurement under reference conditions using the DW2 chamber were approximately 0.6 % which are lower than those for the commercial chamber (Farmer) of 0.89 %.

Conclusions: The obtained results confirm that the DW2 ionization chamber is an accurate tool for measuring absorbed dose to water under reference conditions for therapeutic photon beams. Lower measurement uncertainty will translate into higher precision in monitoring and calibration of the accelerator's output.

1. Introduction

Since 2012, the Central Office of Measures (Główny Urząd Miar, GUM) has been working on the development of a primary ionometric standard for absorbed dose to water in a gamma radiation field of the ^{60}Co. The outcome of this work was the development of a cylindrical graphite ionization chamber. Three chambers of this type were built, the last of which, numbered DW3, took part in the BIPM.RI(I)-K4 key comparisons in 2020 for the absorbed dose to water in gamma radiation field of the nuclide ^{60}Co with a positive result.[1] The changes introduced by the ICRU90 report[2] prompted the initiation of work on developing a primary standard for the radiation quality used in routine radiotherapy. In collaboration with the Holy Cross Cancer Center in Kielce, numerous measurements were conducted using the DW2 ionization chamber (twin to DW3) on clinical beams to achieve this goal. The results of these measurements highlighted the potential for using the ionization chamber developed at GUM for routine dosimetric measurements in clinical beams.

In centers using radiotherapy for cancer treatment, Farmer-type ionization chambers are commonly used for dosimetry

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of high-energy photon beams generated by medical linear accelerators. According to the IAEA TRS 398 report[3] recommendations, the user's chamber is best calibrated for the different beam qualities in a standards laboratory that provides a direct measurement of $N_{D,w,Q}$ or $k_{Q,Q0}$ for those beam qualities (approach a), or b), in Section 4.1.1 of the TRS 398 report). Unfortunately, this approach is limited only to laboratories that have such standards. For this reason, a frequently used approach is to calibrate at ^{60}Co in a secondary standard dosimetry laboratory (SSDL) (approach c), in section 4.1.2 of the TRS 398 report). For the ionization chamber calibrated in this way to be used in high-energy photon beams, a beam quality correction factor, k_Q, must additionally be applied. The factor values can calculated by the user based on the appropriate tables in the IAEA TRS 398 report and the user's measured photon beam quality factor $TPR_{20,10}$.[3] In case no experimental data are available, or it is difficult to measure $k_{Q,Q0}$ directly in the beam quality used clinically, in many cases the correction factor can be calculated according to Appendix II in IAEA TRS 398 report[3] It should be emphasized that the k_Q factors found in the literature for commercially available ionization chambers are determined based on the technical data (*blueprints*) provided by the manufacturer and do not account for differences between individual units. Additionally, the signal measured by the chamber may change over time, which could affect the value of the determined k_Q factor. This factor and other influence quantities values are an additional source of uncertainties in the determination of absorbed dose to water under reference conditions. It deals with the calibration of the user beam and includes the uncertainties associated with the measurement at the reference point in water phantom. The second part of the uncertainty is related with the calibration of the user reference dosimeter in terms of $N_{D,w}$ at the standards laboratory[2]. According to the IAEA TRS 398 report[3] the relative standard uncertainty of the beam quality factor k_Q is equal to 0.6 %, and its incorrect determination may lead to errors in radiation dose determination.

The use of an ionization chamber for which the beam quality correction factors k_Q have been individually determined could reduce the overall standard uncertainty of the dose measurement under reference conditions for high-energy photon beams, as described in the IAEA TRS 398 report.[3] The possibility of improving measurement accuracy motivated the determination of the appropriate factors for the experimental DW2 chamber and the subsequent verification of performance in routine measurements.

2. Materials and methods

2.1. Design of the DW2 ionization chamber

The DW2 ionization chamber has the shape of a cylinder. The chamber consists of an aluminium housing (stem) and three insulated electrodes: a polarizing graphite electrode (outer), a graphite measuring electrode (central), and an aluminum guard electrode (surrounding the lower part of the central one). The schematic diagram of the chamber is shown in **Figure 1**. The dimensions of the individual elements are provided in **Table 1**.

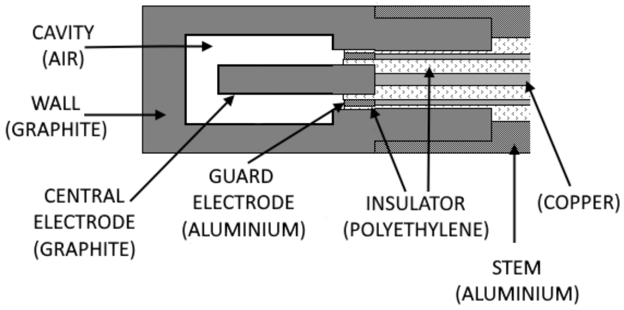

Figure 1. Schematic diagram of the DW2 ionization chamber.

Table 1. Nominal dimensions of the DW2 ionization chamber

Element	Diameter [mm]	Length [mm]
Chamber cavity	7.5	12.5
Central electrode	2.5	10.0

The 2.5 mm wall thickness allows for air kerma measurements in the radiation fields of sources such as ^{192}Ir, ^{137}Cs, and ^{60}Co without the need for additional build-up caps. The nominal volume of the DW2 ionization chamber is 0.506 cm³. The density of the graphite used in the chamber construction was 1.81 g/cm³. This type of chamber is described in detail in reference.[4] The chamber can be connected to an electrometer either directly via a TRIAX connector or via a TRIAX-BNT adapter (for PTW electrometers with a BNT connector) and via a TRIAX-BNC adapter with an additional power cable to the ionization charge and current measurement system described in reference.[5] The latter connection was used in this publication. In this setup, the polarizing voltage is applied to the stem and the graphite wall of the chamber. For measurements in a water phantom, a waterproof sleeve made of polycarbonate with a wall thickness of 1 mm was used. The connection using the TRIAX-BNT adapter was tested with the Unidos Romeo electrometer produced by PTW. In this case, the polarizing voltage is applied to the measuring electrode (a standard solution in ionization chambers used in clinical practice).

2.2. The DW2 chamber characteristics in gamma radiation fields of ^{137}Cs and ^{60}Co

The DW2 ionization chamber was tested in the Ionizing Radiation Laboratory of the Central Office of Measures (GUM) in the gamma radiation fields of the ^{137}Cs and ^{60}Co radionuclides, as described in works.[4,6] The chamber's leakage current (measurement without radiation field) was on average 8 fA. For measurements performed in the gamma radiation field of ^{137}Cs, the chamber required approximately 3-4 measurement series (about 30-40 minutes) from the moment the source was opened to achieve a stable signal. A stable signal is defined as a series of measurements that differs from the mean by less than 0.1 %. For the ^{60}Co radiation field, stability was achieved in a much shorter time — about 10 minutes. In the

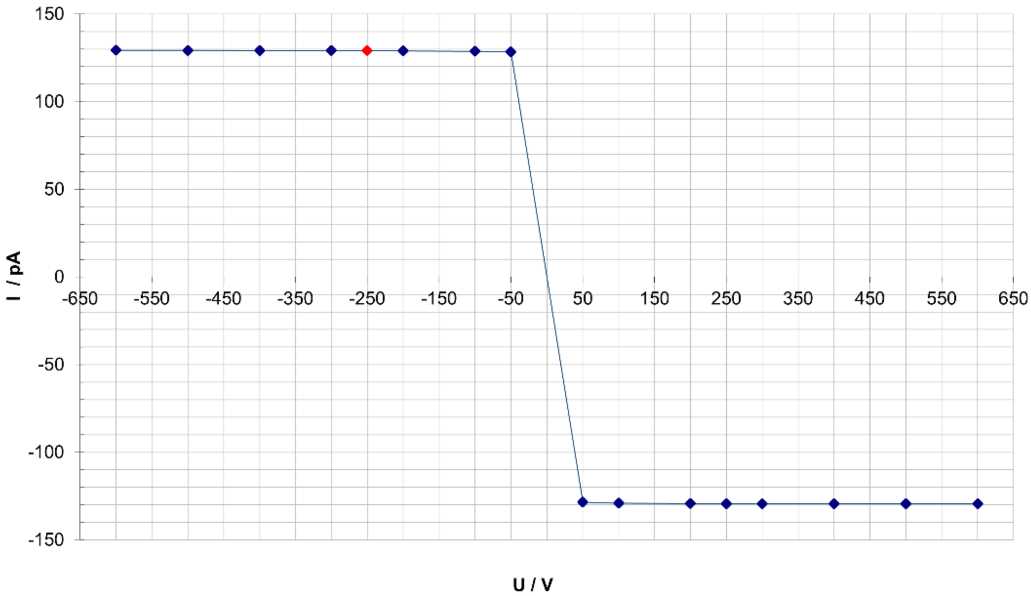

Figure 2. Graph of ionization current as a function of supply voltage for the DW2 chamber.

^{137}Cs gamma radiation field, the measurement time was set to 60 seconds, while for ^{60}Co to 20 seconds. During the measurements, the voltage curve (ranging from -600 V to +600 V) in the ^{60}Co radiation field was determined. For each supply voltage, at least 5 series of 10 independent measurements were performed. The chamber supply voltage was then set to either +250 V or +300 V. The graph showing the relationship between the ionization current, and the supply voltage is presented in **Figure 2**.

During the measurements, the short-term repeatability of the ionization chamber response was checked in the reference gamma radiation fields of the ^{137}Cs and ^{60}Co radionuclides. In series of 10 measurements for the ^{137}Cs radiation field, the standard deviation ranged from 0.05 % to 0.13 %, while for measurements in the ^{60}Co radiation field, the variation was up to 0.07 %.

Long-term stability checks were also conducted during the period 2022-2023 in the gamma radiation field of the ^{60}Co radionuclide, with a relative standard deviation of 0.24 %.

2.3. DW2 ionization chamber calibration

Calibration of the DW2 chamber was performed by the substitution method using the primary standard for absorbed dose to water in a gamma radiation field of ^{60}Co. The source-to-chamber distance was 1 meter, and the chamber was positioned in a water phantom at a depth of 5 g/cm^2. The irradiation field was a square of 10 cm x 10 cm. The calibration was performed using the GUM primary standard for absorbed dose to water.[1,4-7] The absorbed dose to water calibration factor, N_{Dw}, was determined using the following formula:

$$N_{D_w} = \frac{\dot{D}_w}{M_{corr}} \quad (1)$$

where: $\dot{D}_w$ – absorbed dose rate to water, M_{corr} – dosimeter reading corrected for environmental conditions (pressure and temperature).

The result of each calibration measurement is related to the atmospheric pressure of 1013.25 hPa and the air temperature of 20.0 °C. For measurements conducted in different environmental conditions, a correction factor k_{TP} calculated according to the following formula should be used:

$$k_{TP} = \frac{p_0}{p}\frac{T}{T_0} \quad (2)$$

where: p_0 – reference pressure equal to 1013.25 hPa, p – atmospheric pressure during measurements expressed in hPa, T – air temperature during measurements (T = 273.15 + t, where t is the temperature in °C), T_0 – reference temperature equal to 293.15 K.

2.4. Determination of the beam quality correction factors k_Q

The quality correction factors k_Q for different radiation beams were determined using Monte Carlo simulation methods in the Fluka+Flair environment[6] according to the protocol presented in[8-10]. For this purpose, the DW3 chamber model[6], modified to the actual dimensions of the DW2 model, was used together with the IAEAphsp file for the ^{60}Co gamma radiation irradiator Terabalt T-100.[4] The value of the k_Q factor for the different radiation qualities used at the Holy Cross Cancer Center was calculated using the following formula:

$$k_Q = \left(\frac{D_w}{D_{det}}\right)_Q \Bigg/ \left(\frac{D_w}{D_{det}}\right)_{Co} \quad (3)$$

where: D_w – absorbed dose to water at the reference depth, D_{det} – absorbed dose to the detector volume, Q – measurement in the radiation beam of the medical accelerator, Co – measurement in the beam radiation of the ^{60}Co nuclide. The scoring volume was set in two ways: as a 0.25 mm thin disk or as the active volume (cavity) of the detector.

In order to carry out Monte Carlo simulations, the first step was to develop a model of the medical accelerator used at the Holy Cross Cancer Center (Versa HD, Elekta). The model was validated by comparing the obtained dose distributions with measured dose distributions using the Versa HD accelerator. The primary parameter was the compatibility of the $TPR_{20,10}$ values derived from both MC simulation and Holy Cross Cancer Center measurements. Consequently, three independent simulations were conducted to generate IAEAphsp files for 6, 10 and 15 MV photon beams, which were used to determine the beam quality correction factors k_Q for the DW2 ionization chamber.

Three files were generated for three radiation qualities corresponding to acceleration voltages of 6 MV, 10 MV, and 15 MV. The irradiation field was 10 cm x 10 cm with SSD = 90 cm. The IAEAphsp files were used for simulations with the DW2 ionization chamber model. All simulations were performed using the Fluka+Flair program[11] with the transport parameters of: E_{cut} = 521 keV, P_{cut} = 1 keV, with 10^9 histories in 100 cycles. The Monte Carlo simulations provided values for D_w and D_{det}, from which the k_Q correction factors were determined using Equation (4). The k_Q factors were determined with a relative standard uncertainty of 0.43 %. The standard uncertainties were determined in accordance with the JCGM 100:2008 report.[12]

2.5. Determination of correction factors for saturation k_s and polarization k_{pol} in high-energy photon beams

The signal measured by the ionization chamber is an underestimated value because some of the ions generated within the chamber cavity undergo recombination and thus do not reach the collecting electrode. Therefore, an additional correction factor must be introduced to account for the lack of full chamber saturation. It is expected that the obtained value of the recombination correction factor will be greater than one. According to the IAEA TRS 398 report[2] the correction factor for incomplete saturation for accelerator pulsed beams was determined using the two-voltage method:

$$k_s = a_0 + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2 \qquad (4)$$

where: a_0, a_1, a_2 – constants provided in the IAEA TRS 398 report, M_1, M_2 – the chamber signal measured at voltages V_1 and V_2, respectively.

Each ionization chamber operates at a so-called operating voltage and operating polarization. For the DW2 ionization chamber, the determined (according to chapter 2.2) operating voltage value is +300 V. Positive polarization means that a positive potential is applied to the central electrode. The measured ionization current changes in absolute value when the polarization of the voltage applied to the chamber is reversed. This phenomenon is known as the polarization effect and has a significant impact on the measurement of ionization current in photon beams. It is assumed that the average of the measurements at both polarizations is equal to the charge collected by the collecting electrode from the chamber cavity[10]:

$$k_{pol} = \frac{|M_+| + |M_-|}{2M} \qquad (5)$$

where: M_+ and M_- are the electrometer readings for positive and negative polarizations, respectively, and M is the electrometer reading for the routinely used polarization.

The standard uncertainties for k_Q, k_s and k_{pol} coefficients were determined according to the JCGM report 100: 2008.[12]

2.6. Verification of the DW2 ionization chamber performance for absorbed dose to water measurements under reference conditions for high-energy photon beams

To verify the performance of the DW2 ionization chamber and the accuracy of the determined calibration factor and correction factors, comparative measurements of absorbed dose to water were conducted using a commercially available Farmer-type ionization chamber, model 30013, connected to a PTW Romeo electrometer. Measurements were performed in a PTW MP1 water phantom under reference conditions (SSD = 90 cm, depth = 10 cm, field size 10 cm x 10 cm) for photon beams with accelerating potentials of 6, 10, and 15 MV, for 200 MU (monitor units). For each chamber and each photon energy, 10 measurements were performed independently. Standard uncertainties for the obtained dose values were calculated and compared with each other.

The agreement of the results was assessed using the metrological compatibility test[13]:

$$\zeta\left(D_{DW2} - D_{Farmer}\right) = \frac{\left|D_{DW2} - D_{Farmer}\right|}{\sqrt{u^2\left(D_{DW2}\right) + u^2\left(D_{Farmer}\right)}} \leq 2 \qquad (6)$$

where: D_{DW2} and $u(D_{DW2})$ are the absorbed dose to water and its standard uncertainty measured with the DW2 ionization chamber, respectively, while D_{Farmer} and $u(D_{Farmer})$ are analogous quantities measured with the commercially available Farmer-type ionization chamber, model 30013, from PTW.

According to the test used, to conclude that two values are consistent with each other (at a 95 % confidence level), the absolute difference between their values should be less than or equal to twice the square root of the sum of the squares of their standard uncertainties.

3. Results

The calibration factor value for the DW2 chamber determined in the ^{60}Co source radiation field, according to the procedure described in section 2.4, was N_{Dw} = 5.964·10^7 Gy/C with an expanded uncertainty of 0.036·10^7 Gy/C (for the coverage factor k = 2). As a result, the relative expanded uncertainty in this measurement was 0.6 %. During this calibration procedure, the absorbed dose rate to water was $7.12 \cdot 10^{-3}$ Gy/s.

In the presented work, it is crucial that the conducted MC simulations of specific quantities and the results of experimental measurements compared with them were performed for radiation beams with the same values of beam quality indexes $TPR_{20,10}$. The values of these factors for the high-energy photon beams used in the Holy Cross Cancer Center and the factors generated by Monte Carlo methods for the model of the used accelerator (based on the manufacturer's data) are presented in **Table 2**.

Table 2. Beam quality indices $TPR_{20,10}$ for high-energy photon beams produced by the Versa HD linear accelerators from Elekta installed in the Holy Cross Cancer Center and simulated MC data for model of this accelerator.

Photon energy [MV]	$TPR_{20,10}$ (experimental)	$TPR_{20,10}$ (MC simulation)	Difference
6	**0.679**	**0.675**	**-0.6 %**
10	**0.732**	**0.723**	**-1.2 %**
15	**0.759**	**0.761**	**0.3 %**

The maximum difference between the beam quality index $TPR_{20,10}$ measured for the accelerator and the index obtained from Monte Carlo simulations was -1.2 % for a 10 MV photon beam. Considering that the developed Monte Carlo model of the accelerator head is highly simplified, we considered these differences to be acceptable, especially taking into account the recommendations for quality assurance in medical accelerators[14], which suggest that the consistency of the beam quality index measured during annual tests should be within ±1.0 %.

The results of absorbed dose to water measurements using the DW2 ionization chamber in the fields of photon beams of 6, 10, and 15 MV are presented in **Table 3** together with the parameters influencing the dose. The table contains values for the average charge measured by the chamber, corrected for pressure and temperature (Q_{corr}), the calibration factor (N_{Dw}), beam quality correction factors (k_Q), correction factors for saturation (k_s) and polarization (k_{pol}), as well as the calculated absorbed dose (D_w) calculated according to the final formula:

$$D_w = Q_{corr} N_{Dw} k_Q k_s k_{pol} \quad (7)$$

All values are presented with relative standard uncertainties (u_r) calculated according to the JCGM 100:2008 report.[12]

Table 4 presents the results of absorbed dose to water measurements performed using the commercial ionization chamber model 30013 from PTW. The table contains information similar to this in **Table 3**.

Table 5 presents the results of the absorbed doses to water (D_w) and their relative standard uncertainties (u) for the DW2 ionization chamber and the commercial Farmer-type ionization chamber for photon beams of 6, 10, and 15 MV, including the percentage differences and the values of the metrological compatibility coefficient ζ calculated according to Equation (6).[13]

Table 3. Values and relative standard uncertainties (u_r) of all the parameters necessary for calculating the absorbed dose to water for the DW2 ionization chamber.

Photon energy [MV]	**6**		**10**		**15**	
Factor	Value	u_r	Value	u_r	Value	u_r
Q_{corr} [nC]	33.7	0.11 %	33.8	0.11 %	34.0	0.11 %
N_{Dw} [Gy/C]	5.96E+07	0.30 %	5.96E+07	0.30 %	5.96E+07	0.30 %
k_Q	0.999	0.43 %	0.993	0.34 %	0.988	0.34 %
k_s	1.001	0.08 %	1.002	0.02 %	1.002	0.06 %
k_{pol}	0.9994	0.03 %	0.9995	0.04 %	0.9995	0.02 %
D_w [Gy]	2.01	0.54 %	2.00	0.47 %	2.01	0.47 %

Table 4. Values and relative standard uncertainties (u_r) of the all parameters necessary for calculating the absorbed dose to water for the Farmer-type ionization chamber, model 30013 from PTW.

Photon energy [MV]	**6**		**10**		**15**	
Factor	Value	u_r	Value	u_r	Value	u_r
Q_{corr} [nC]	37.9	0.11 %	38.1	0.15 %	38.3	0.12 %
N_{Dw} [Gy/C]	5.36E+07	0.64 %	5.36E+07	0.64 %	5.36E+07	0.64 %
k_Q	0.988	0.60 %	0.976	0.60 %	0.964	0.60 %
k_s	1.002	0.03 %	1.004	0.05 %	1.004	0.04 %
k_{pol}	1.001	0.03 %	1.000	0.05 %	1.001	0.04 %
D_w [Gy]	2.01	0.89 %	2.00	0.89 %	1.99	0.89 %

Table 5. Comparison of absorbed dose to water measurements using the DW2 ionization chamber and the Farmer-type chamber (model 30012, PTW).

Photon energy [MV]	**6**		**10**		**15**	
Factor	Dw [Gy]	u_r	Dw [Gy]	u_r	Dw [Gy]	u_r
DW2	2.01	0.54 %	2.00	0.47 %	2.01	0.47 %
30013	2.01	0.89 %	2.00	0.89 %	1.99	0.89 %
Difference	-0.1 %		0.2 %		0.7 %	
ζ	-0.1		0.1		0.6	

4. Discussion and conclusions

The comparison of absorbed dose to water measurements under reference conditions between the experimental DW2 ionization chamber and the commercially available Farmer-type ionization chamber (model 30013, PTW), for high--energy photon beams with accelerating potentials of 6, 10, and 15 MV, as shown in **Table 5**, indicates that the DW2 chamber, along with its calibration factor N_{Dw} and the determined correction factors for beam quality k_Q, as well as correction factors for saturation and polarization, can be successfully used for routine calibration measurements of clinical linear accelerators. The relative dose differences of these ionization chambers are -0.1 %, 0.2 % and 0.7 % for photon beams of

6, 10 and 15 MV, respectively. All metrological compatibility coefficients are significantly below the value of 2, indicating a very good agreement of the measurement results. The largest difference is observed for the 15 MV photon beam and it is difficult to justify this discrepancy based on the obtained results.

It is particularly noteworthy that the total relative standard uncertainties of the absorbed dose measurements to water using the DW2 chamber are less than 0.6 %. By comparison, the same uncertainties for the commercially available Farmer-type chamber are at the level of 0.89 %. One reason for this difference is the lower uncertainty of the calibration factor for the DW2 chamber, which was calibrated against GUM primary standard. In contrast, commercial ionization chambers are usually calibrated against secondary standards, which have higher uncertainties than primary standards. The second reason for the difference mentioned above is the lower value of the standard uncertainty of the beam quality factor k_Q for the DW2 chamber equal to 0.43 %. This is because this factor was individually determined for this chamber using Monte Carlo methods based on numerical models of photon beams matched to beams used in clinical practice. For the commercial Farmer model 30013, the k_Q factor was determined according to the formalism described in IAEA TRS 398[3], based on the relevant tables. According to the report, the uncertainty of this factor is 0.6 %, contributing the most to the overall standard uncertainty of the dose measurement. The standard uncertainties for k_s and k_{pol} were at a similar level for both chambers.

The lower measurement uncertainty of the DW2 chamber with individually determined k_Q factors compared to commercially available Farmer-type ionization chambers, based on the formalism described in IAEA TRS 398[3], will translate into greater precision in accelerator performance monitoring and calibration, and consequently, greater accuracy in dose delivery to the patient.

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