Evaluating the Impact of Ionization Chamber-Specific Beam Quality Correction Factor in Dosimetry of Filtered and Unfiltered Photon Beams

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Abstract

Aim: The response of ionization chamber changes when used at beam quality Q which is different from beam quality Q_o (usually ^{60}Co) that was used at the time of its calibration. Hence, one needs to apply beam quality correction factor ($k_{Q, Qo}$) during dosimetric measurements. However, $k_{Q, Qo}$ data are unavailable for novel ion chambers in the literature. Moreover, most of such data do not differentiate between filtered (flat) and unfiltered (unflat) beams. In addition, literature-based data do not differentiate among different pieces of the ion chambers of the same make and model. Hence, the purpose of our study was to determine the ion chamber-specific experimental values of $k_{Q, Qo}$ and to evaluate their impact in dosimetry. **Materials and Methods:** In this work, the value of $k_{Q, Qo}$ were measured for six ionization chambers of three different types in 6, 10, and 15 MV filtered (with flattening filter [WFF]) as well as 6 and 10 MV unfiltered (flattening filter free [FFF]) photon beams. The measured values of $k_{Q, Qo}$ were compared with Monte Carlo-calculated values available in the literature. The uncertainties in measurement of $k_{Q, Qo}$ values were also evaluated. **Results:** For 6 MV FFF beam, the measured value of $k_{Q, Qo}$ was found to be consistently lower than 6 MV WFF beam for all Sun Nuclear Corporation ion chambers, while it was higher as per the theoretical data. The inter-chamber variation in $k_{Q, Qo}$ values was observed for the same model of the ion chambers. The maximum difference between absolute dose values on using the theoretical and experimental $k_{Q, Qo}$ values was up to 3.23%. **Conclusion:** The measured absolute dose values by the ion chamber of a given make and model were found different due to the use of its theoretical and experimental $k_{Q, Qo}$ values. Furthermore, the variation in response of different pieces of ion chambers of the same make and model cannot be accounted for theoretically, and hence, the use of theoretical $k_{Q, Qo}$ data may introduce an inherent error in the estimation of absorbed dose to water. This necessitates the use of measured value of $k_{Q, Qo}$ for each ionization chamber.

Keywords: Beam quality correction factor, flattening filter free, ionization chamber, uncertainty

Introduction

Radiation dosimetry is essential to make sure that the intended radiation dose is delivered to the patient within acceptable tolerance limit. The in-phantom dosimetry is carried out before the delivery of prescribed radiation dose to the patients. Ionization chamber-based dosimetry is widely performed in radiotherapy (RT) setups. The code of practice (CoP) prescribed in the International Atomic Energy Agency (IAEA) Technical Report Series (TRS) 398[1] and American Association of Physicists in Medicine (AAPM) Task Group (TG) 51[2] is used worldwide.[1,2] However, these CoPs are more than two decades old during which many new developments have taken place in RT. Clinical implementation and continuous increase in the use of flattening filter-free (FFF) photon beams due to their associated advantages[3] and treatment via small fields are few such examples. To fulfill the requirements of changed scenario of RT, AAPM has provided an addendum to TG-51 report in 2014 to include various aspects of dosimetry in FFF beams.[4] Furthermore, IAEA and AAPM have jointly

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published TRS-483 to provide a CoP for small-field dosimetry which is also applicable for conventional FFF/with flattening filter (WFF) beam dosimetry.[5]

The data available for $k_{Q, Qo}$ (or k_Q, if the calibration quality (Q_o) is ^{60}Co) values in the literature are limited and are unavailable for novel ion chambers.[1,2,4,5] Therefore, nowadays, vendors of ionization chambers provide k_Q values which are either Monte Carlo (MC) calculated or experimentally measured for new ion chambers.[6,7] For example, Sun Nuclear Corporation (SNC) provided k_Q values for SNC600c ion chamber by contracting the services of the National Research Council of Canada (NRCC). NRCC reported k_Q values for this ion chamber through MC simulation for clinical photon beams. However, the SNC125c ion chamber does not have an equivalent NRCC report and hence the SNC recommends to obtain the corresponding k_Q via the method of cross-calibration. Similarly, the experimentally measured k_Q values for FAR 65GB ionization chamber are provided by its vendor (Rosalina Instruments India Private Limited, Mumbai, India).[7] However, the given k_Q values are for 6 and 18 MV filtered clinical photon beams only and are based on an experimental study of a single ion chamber.[7] As per TRS-398, such vendor-provided k_Q values are not allowed for use in dosimetry since the measurements involved a single ion chamber only.[1] Although it is suggested to obtain k_Q for new ionization chambers either by cross-calibration or from the manufacturer,[8] it is recommended to use the measured value of k_Q since the theoretical values do not incorporate inter-chamber variation and such values are dependent on the chamber specifications.[1,2,4]

Inherent assumption in using the calculated k_Q values is that all the ion chambers of a given make and model behave in the same way and their response is independent of the dose rate of radiation beam. Comparison of calculated and measured k_Q values is encouraged by TG-51 addendum[4] as a very limited number of Primary Standard Dosimetry Laboratories are available in the world that can provide direct calibrations in clinical photon beams and thus chamber-specific $k_{Q, Qo}$ values. Furthermore, with the availability of more accurate MC calculation systems and updated key data for the stopping power ratio and mean excitation energies, given by ICRU Report 90 for radiation dosimetry,[9] recent studies quoted deviations of up to 1.0% in k_Q values compared to TRS-398 and TG-51 data.[10]

Therefore, the objective of this study was to determine ionization chamber-specific experimental $k_{Q, Qo}$ (or k_Q since the calibration beam quality is ^{60}Co) values for six ion chambers (of three different types) at various beam qualities including both filtered (WFF) and unfiltered (FFF) clinical photon beams and to study their effect in clinical dosimetry.

MATERIALS AND METHODS

Beam quality correction factor

The calibration coefficient in terms of absorbed dose to water at the beam quality Q_o (usually ^{60}Co), $N_{D, W, Qo}$, provided by the standard laboratory needs a correction factor to remain valid when used at a beam quality Q. This correction factor is known as beam quality correction (BQC) factor ($k_{Q, Qo}$), and it is a chamber-specific correction factor. It corrects the response of an ionization chamber due to the difference between the beam quality that was used at the time of ion chamber calibration, Q_o, and the user's beam quality, Q. Mathematically, for beam quality, Q.[1,2]

$$N_{D, W, Q} = N_{D, W, Qo} \times k_{Q, Qo} \qquad (1)$$

Measurement of k_Q

TRS-398 is the CoP for the dosimetry of external beam radiotherapy (EBRT). Experimental measurements were done using two EBRT machines, Theratron 780 telecobalt machine (TeamBest Inc., USA) and TrueBeam medical electron linear accelerator (linac) (version 2.7, Varian Medical System, Palo Alto, USA). The normal treating distance of these machines is 80 cm and 100 cm, respectively. The performance (including output) of both telecobalt machine and medical electron linac was verified as a part of quality assurance tests to make sure that the measurements are not affected by any underlying issue of either EBRT machine.

Five ion chambers of SNC (two SNC600c models and three SNC125c models) and one ionization chamber of IBA (IBA Razor) were used in this study. The technical details of these ion chambers are given in Table 1. All of these ion chambers were calibrated at the Standard Dosimetry Laboratory and have valid calibration coefficients at the time of this study.

The slab phantom (Gammex solid water®) was used for measurements to reduce the setup time since its use is allowed for relative measurements.[5] The cross-calibration procedure mentioned in TRS-483 was used in this study because this method is equivalent to the cross-calibration procedure mentioned in TRS-398 for the machine-specific reference (msr) field of 10 cm × 10 cm.[5] However, the notations used in equations of TRS-398 are more pronounced; therefore, equations of TRS-398 have been reproduced here.

The isocentric setup (which is also called source-to-axis distance [SAD] setup) was used for all the experimental measurements. The reference point of ionization chamber was placed at the reference depth of 10 cm (9.97 cm water equivalent depth[5]), and the reference field of 10 cm × 10 cm was used for irradiations. The measurements were carried out using cobalt-60 gamma rays from Theratron 780 telecobalt machine (SAD = 80 cm) and five X-ray energies (WFF: 6, 10, and 15 MV; FFF: 6 and 10 MV) from TrueBeam linac (SAD = 100 cm). The measurements were done at the dose rate of 500 monitor units (MU)/min, 1200 MU/min, and 2000 MU/min for WFF beams, 6 MV FFF beam, and 10 MV FFF beam, respectively, on linac while the output of telecobalt machine was 126.97 cGy/min (for SAD setup) at the time of measurements. All the ionization chambers were preirradiated with 5 Gy dose both on linac and telecobalt machine for attaining the thermal and charge stability.

Table 1: Technical details of ionization chambers used in this work			
Parameter	**SNC600c**	**SNC125c**	**IBA Razor**
Shape	Cylindrical	Cylindrical	Cylindrical
Active length (cm)	2.270	0.705	0.360
Active volume (cm³)	0.600	0.108	0.010
Water-proof	Yes	Yes	Yes
Calibration laboratory	Accredited Dosimetry Calibration Laboratory, MD Anderson Cancer Centre	Accredited Dosimetry Calibration Laboratory, MD Anderson Cancer Centre	IBA Dosimetry Laboratory

MD: Monroe dunaway

As per TRS-398, the absorbed dose to water at beam quality Q at reference point is given by,

$$D_{w, Q} = M_Q N_{D, w, Q} \quad (2)$$

where M_Q is electrometer reading at beam quality Q corrected for temperature–pressure ($k_{T, p}$), polarity (k_{pol}), ion recombination (k_{sat}), electrometer calibration factor (k_{elec}), and humidity (k_h) corrections. $N_{D, w, Q}$ is the calibration coefficient in terms of absorbed dose to water at beam quality Q.

All chambers used in this study were calibrated directly at the Standard Dosimetry Laboratory at reference quality Q_o (^{60}Co) as mentioned in Table 1. Although chambers with volume of 0.6 cm³ are recommended for reference dosimetry of filtered photon beam,[1] it is not so for unfiltered photon beam as the lateral beam profile is nonuniform and reference chamber with a shorter length and typical volume between 0.1 cm³ and 0.3 cm³ is recommended.[5] SNC600c_1 and SNC125c_1 were thus used as the reference chamber for filtered and unfiltered beams, respectively. To deliver 1 Gy dose on linac, MC-calculated $k_{Q, Qo}$ values of SNC600c chamber were used[6] for filtered beams and $k_{Q, Qo}$ values of PTW 31002 flexible ion chamber (equivalent chamber, as quoted by the vendor) were used[1] for unfiltered beams. However, no such $k_{Q, Qo}$ value was required for telecobalt machine.

For each set of measurement, beam ON time was set to deliver 1 Gy dose at the isocenter on telecobalt machine. Similarly, MUs were set to deliver 1 Gy dose at the isocenter for an identical measurement setup on linac. Since fixed dose of 1 Gy was delivered both on telecobalt machine and linac, hence

$$D_{w, Q} = D_{w, Qo} \quad (3)$$

For cross-calibration, two ionization chambers are placed successively in the radiation beam and are irradiated with the same dose to obtain the calibration coefficient for the field ionization chamber using the following equation: [1,5]

$$N_{D, w}^{\ field} = (M_{ref}/M_{field}) N_{D, w}^{\ ref} \quad (4)$$

where M_{ref} and M_{field} are the corrected electrometer readings for reference and field ionization chambers, respectively, and $N_{D, w}^{\ ref}$ is the calibration coefficient for the reference ionization chamber.

In our study, the same ionization chamber that was calibrated at the Standard Dosimetry Laboratory (and hence can be used as a reference ionization chamber) was irradiated with the same dose both on the linac and telecobalt machine with identical measurement setup. Hence, for our case, using equations (2), (3) and the concept of cross-calibration, the following equation was obtained which is analogous to equation (4) and can be used to obtain the value of calibration coefficient at beam quality Q,

$$N_{D, w, Q} = (M_{Qo}/M_Q) N_{D, w, Qo} \quad (5)$$

where M_{Qo} and M_Q are the corrected electrometer readings at beam quality Q_o and Q respectively, and $N_{D, w, Qo}$ is the calibration coefficient at beam quality Q_o which is provided by the Standard Dosimetry Laboratory.

The value of $N_{D, w, Q}$ so obtained was used in equation (1) to calculate the value of chamber-specific BQC factor, $k_{Q, Qo}$. This procedure was repeated for all the ionization chambers and for all clinical photon beams available on the linac. The measured values of k_Q were compared with the corresponding theoretical values provided by the supplier/manufacturer.

Common correction factors

The electrometer reading was corrected with temperature–pressure correction factor ($k_{T, p}$), polarity correction factor (k_{pol}), ion recombination correction factor (k_{sat}) using the relations available in IAEA TRS-398. For the sake of completeness, these relations are given below,

$$k_{T,P} = ((T + 273.2)/(T_o + 273.2)) (P_o/P) \quad (6)$$

where T and *P* are measured values of air temperature and pressure, respectively, and T_o and P_o are reference values of air temperature (20°C) and pressure (1013.2 mbar), respectively.

$$k_{pol} = (|M_+|+|M_-|)/2M \quad (7)$$

where M_+, M_-, and M are electrometer readings at positive, negative, and commonly used polarity, respectively. Since + 300 Volts (V) is used for routine measurements at our center, so measurements were done at ± 300 V to find the value of k_{pol}.

$$k_{sat} = a_o + a_1(M_1/M_2) + a_2(M_1/M_2)^2 \quad (8)$$

$$k_{sat} = ((V_1/V_2)^2 - 1)/((V_1/V_2)^2 - (M_1/M_2)) \quad (9)$$

where a_o, a_1, and a_2 are the quadratic fit coefficients for k_{sat} and are available in TRS-398, and M_1 and M_2 are the electrometer readings at higher voltage (V_1 = +300 V) and lower voltage (V_2 = +100 V), respectively.

Electrometer calibration factor (k_{elec}) is not required in the case of cross-calibration as the chamber and electrometer are calibrated together as a single unit and therefore were not applied. Humidity correction factor (k_h) was also not applicable since calibration factors were not referred to dry air.

Volume averaging correction factor (k_{vol}) in the case of flattening filter-free beams

The absorbed dose to water is measured at a point, but the ionization chamber has a finite length and volume and the reading of an ionization chamber is the average response over its active volume. Since the beam profile of an unfiltered beam is of nonuniform intensity over the chamber length, so k_{vol} was applied to correct the response of the ionization chamber. The influence of this correction factor increases with the length of the ionization chamber because the beam profile is centrally peaked for unfiltered photon beams. k_{vol} was calculated using the formula mentioned in TRS-483[5] and applied to the dosimeter readings of both 6 and 10 MV unfiltered beams.

Phantom dose conversion factor ($k_{Qmsr}^{w, plastic}$)

Since solid water slab phantom was used instead of water, therefore, phantom dose conversion factor was used to convert the electrometer reading measured in slab phantom into absorbed dose to water. The value of $k_{Qmsr}^{w, plastic}$ increases with increase in $TPR_{20,10}$ value and is available in TRS-483[5] for Gammex solid water slab phantom used in this study for machine-specific reference field of 10 cm × 10 cm.

Measurement of beam quality index

$TPR_{20,10}$ is the beam quality index for high-energy photon beam. Since $TPR_{20,10}$ is related to beam energy, k_Q, k_{vol}, and $k_{Qmsr}^{w, plastic}$, hence, it was also measured for all energies as per the procedure mentioned in TRS-398[1] and the variation of k_Q with $TPR_{20,10}$ was plotted for all the chambers. Being a ratio, $TPR_{20,10}$ is independent of the ionization chamber used for measurement, and therefore, the measurements were done with only one ion chamber (SNC600c_1).

Impact of chamber-specific $k_{Q, Qo}$ measurement

The dose at the reference depth of 10 cm in water was calculated using 10 cm × 10 cm field size for each of the photon beam of TrueBeam linac using two different values of $k_{Q, Qo}$ (one measured in this work and the other recorded from the vendor-provided reference to the published data). The difference in dose for the simple clinical condition due to the use of two different values of $k_{Q, Qo}$ was quantified.

Uncertainty budget

The uncertainty is the part of experimental studies, and hence, it is essential to estimate the contribution of the uncertainty in the final result.[11-13] For measurement of absorbed dose to water, the uncertainty arises out of chamber positioning inside the phantom, phantom positioning with respect to the radiation source, environmental conditions, dosimeter response, etc. All these components were assumed to be uncorrelated and assessed separately. Finally, the combined standard uncertainty ($k = 1$) was estimated.[4]

RESULTS

The polarity effect for SNC600c and SNC125c chambers was negligibly small (k_{pol} found to be within 1.000 ± 0.002) as expected for photon beams. However, IBA Razor chamber showed anomalous behavior for polarity as shown in Table 2. The recommended range of polarity correction is $\pm 0.4\%$ with maximum variation of 0.5% within the entire range of clinical photon beams, including ^{60}Co.[4] The values of k_{pol} at various beam qualities are given in Table 2 for IBA Razor chamber, which indicate that it must not be used for reference dosimetry. This behavior of IBA Razor chamber confirms the statement of AAPM TG-51 addendum that ionization chambers with sensitive volume < 0.05 cc show anomalous polarity effect which are not fully explained at present quoting the report of McEwen.[4] For ^{60}Co, the value of k_{pol} was not measured and was taken to be 1 since the calibration laboratory had not corrected for polarity and the same voltage with the same polarity was used for measurements as that was used at the time of calibration.[1]

The average measured values of k_{sat} for 6 FFF and 10 FFF beams were 1.007 and 1.012, respectively, for SNC chambers, while for 6 WFF, 10 WFF, and 15 WFF beams, the average values of k_{sat} were 1.004, 1.004, and 1.006, respectively. The ion recombination correction factor was found to be higher for FFF beams as expected due to greater ion recombination owing to the peaked beam profiles. However, unexpectedly lower value of k_{sat} was obtained for 10 FFF beam with IBA Razor chamber as shown in Table 2. However, the values of ion recombination correction factor were well within recommended working limit of 1.050[2,4] for all the chambers including IBA Razor chamber.

For FFF beams, k_{vol} was estimated to be 1.0 both for IBA Razor and SNC125c ionization chambers due to their small length (<1 cm). Hence, no volume averaging correction factor is required for these chambers up to 10 MV FFF beam. Conversely, in the case of SNC600c ion chambers, the value of k_{vol} was estimated to be 1.002 and 1.004 for 6 MV FFF and 10 MV FFF beams, respectively, owing to a greater chamber length of 2.27 cm.

Figure 1 shows the variation of BQC factor with beam quality index for all ionization chambers used in this study, where it can be seen that for all SNC ion chambers, the measured value of $k_{Q, Qo}$ for 6 MV FFF beam is lower than 6 MV WFF beam, while it is higher as per the theoretical data. This provides

Table 2: Measured values of k_{pol} and k_{sat} for IBA Razor chamber

Energy (MV)	k_{pol}	k_{sat}
6 FFF	0.995	1.012
6 WFF	0.985	1.005
10 FFF	0.996	1.005
10 WFF	0.987	1.005
15 WFF	0.984	1.008

FFF: Flattening filter free, WFF: With flattening filter

further support to the results of some of the recent studies which have suggested the need of revising $TPR_{20,10}$-based $k_{Q, Qo}$ values available in TRS-398 since $TPR_{20,10}$ is not much sensitive to spectral variation of photon beam.[14-16] The use of directly measured $k_{Q, Qo}$ values is preferred[1] and is supported by the observed inter-chamber variation as shown in Figure 1. As a result of this difference between the theoretical and experimental values of $k_{Q, Qo}$, a difference in absorbed dose to water was also noticed and is presented in Table 3. This difference in absorbed dose is due to ionization chamber-specific radiation response which is absent in theoretical $k_{Q, Qo}$ values. A study has found $k_{Q, Qo}$ value for an ionization chamber by using both experimental and MC methods and recommended to use the averaged value.[17]

The difference between absolute dose values obtained using the measured and theoretical $k_{Q, Qo}$ value was found up to 3.23% for IBA Razor chamber [Table 3]. The inter-chamber variation in $k_{Q, Qo}$ values was observed for the same model of ionization chambers as shown in Figure 1. Consequently, the differences in $k_{Q, Qo}$ values resulted in difference of up to 2.06% in the measured absorbed dose to water for SNC125c ionization chamber as shown in Table 3, if theoretical value of $k_{Q, Qo}$ was used instead of chamber-specific measured value.

Figure 1: Beam quality correction factor, $k_{Q, Qo}$, as a function of beam quality index, $TPR_{20,10}$ for (a) SNC600c, (b) SNC125c, and (c) IBA Razor ionization chambers. SNC: Sun Nuclear Corporation

The uncertainty budget for the estimation of $k_{Q, Qo}$ is given in Table 4. The combined uncertainty was calculated considering the uncertainty contribution of all the components to be uncorrelated.

DISCUSSION

This study was done to practically demonstrate the need of using chamber-specific k_Q values. Although several studies have been done in past to find k_Q values for different ionization chambers either by MC simulation or experimental method,[10,14-19] none of these studies reported inter-chamber variation in k_Q values and its corresponding effect on the absolute dose measurement for the same model of ionization chamber as presented in Figure 1 and Table 3, respectively. Moreover, recent studies have reported the need for an update of k_Q values, quoting different k_Q values from TRS-398.[10,12,14,15] Furthermore, in the case of unfiltered beam, the k_Q values are expected to be different from filtered beam for a given nominal beam energy, due to reduced water-to-air stopping power ratios, different ionization chamber perturbation correction factors, volume averaging correction factor, and reduced scatter component at the reference point.[5] A comparison study between WFF and FFF beams reported higher discrepancies in k_Q values if $TPR_{20,10}$ (from TRS-398) was used as the beam quality index as compared to %dd $(10)_x$ (from TG-51).[19] Some other studies even showed that the kQ value for unfiltered beam does not follow the same relation with $TPR_{20,10}$ as the filtered beam does[10,18] and the same can be observed from figure 1. Table 3 shows large variation in absorbed dose for IBA Razor chamber. The possible reason for this variation is the experimentally observed anomalous behavior of polarity effect [Table 2] obtained with IBA Razor chamber. The addendum to AAPM TG-51 report also indicated similar behavior for small-volume chambers (<0.05 cc) stating that such chambers show abnormal polarity corrections that are not fully explained at present.[4]

The absorbed dose to water is measured by aligning the reference point of the ion chamber with the point of interest in the water assuming that the local environment around the point of interest is undisturbed due to the presence of the chamber. However, the presence of the chamber disturbs the radiation fluence and various perturbation corrections are required to correct for this deviation from the ideal condition. Theoretically, these perturbation correction factors are included in BQC factor along with water-to-air stopping power
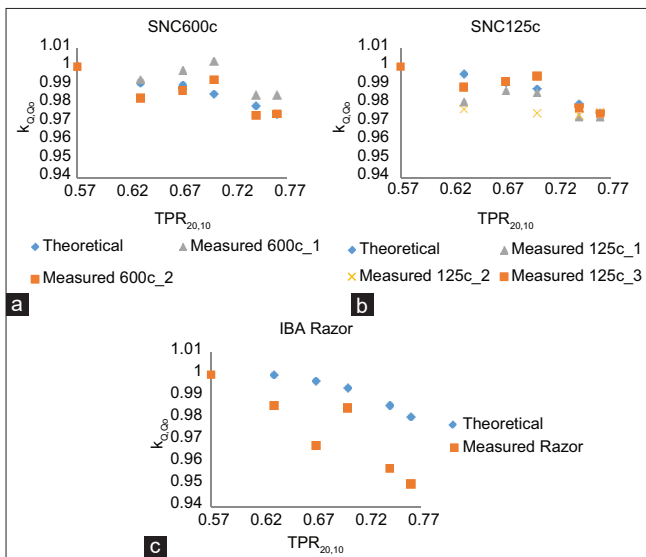
Table 3: Difference in absorbed dose to water if theoretical $k_{Q, Qo}$ value was used instead of measured $k_{Q, Qo}$

Energy (MV)	Difference in absorbed dose to water (%)					
	600c_1	600c_2	125c_1	125c_2	125c_3	RAZOR
6 FFF	−0.20	0.82	1.53	1.95	0.71	1.42
6 WFF	−0.80	0.31	0.41	−0.10	−0.10	3.01
10 FFF	−1.79	−0.80	0.22	1.36	−0.70	0.93
10 WFF	−0.58	0.55	0.76	0.65	0.24	2.98
15 WFF	−1.09	−0.06	0.25	−0.06	0.04	3.23

FFF: Flattening filter free, WFF: With flattening filter

Table 4: Uncertainty budget for the estimation of beam quality correction factor with relative standard uncertainty, k=1

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
SAD		0.10
Field size		0.10
Electrometer reading	0.12 (SNC600c)/0.10 (SNC125c)/0.38 (IBA Razor)	<0.01
k_{pol}	0.01 (SNC600c)/0.01 (SNC125c)/0.25 (IBA Razor)	<0.01
k_{sat}	0.18 (SNC600c)/0.12 (SNC125c)/0.12 (IBA Razor)	<0.01
$k_{T, P}$		0.10
k_{vol}		0.05
$k_{Qmsr}^{w, plastic}$		0.30
k_{h}		0.15
$N_{D, w, Qo}$		1.30 (SNC chambers, k=1)/2.20 (IBA Razor, k=2)
Long-term stability of chamber		0.05
Tele-therapy machine output stability		0.00 (^{60}Co)/0.05 (linac)
Cross-calibration step		0.10
Quadratic summation	0.22 (SNC600c)/0.16 (SNC125c)/0.47 (IBA Razor)	1.36 (SNC chambers, k=1)/1.17 (IBA Razor, k=1)
Combined uncertainty	1.38 (SNC600c)/1.37 (SNC125c)/1.26 (IBA Razor)	

ratios both in calibration and user beam qualities. Recent publications used ICRU 90 key data and provided modified values of k_Q based on MC simulations, which are up to 0.35% different from the previously documented values as per TRS-398.[10] In spite of the relevance of MC study results, such studies are limited by geometries of both ionization chambers and linac beams. Experimental determination of k_Q values is essential to know the behavior of an individual chamber in real clinical photon beams. In addition to the measured quantity, the associated uncertainty should also be evaluated. As per TRS-398, the uncertainty contribution of using the theoretical values of k_Q is 1.00% of the total 1.50% standard relative uncertainty in determining the absorbed dose to water. Hence, this CoP also encourages the use of measured k_Q values. In our study, the estimated relative standard uncertainty of k_Q was found up to 1.38% for SNC600c chamber as shown in Table 4.

The theoretical expression for $k_{Q, Qo}$ depends on the ratios of water-to-air stopping power ratio, perturbation factors, and the average energy required to create an ion pair in air at the qualities Q and Q_o. Beyond the depth of maximum dose, all these quantities can be thought to be independent of the depth as per TRS-398. Since our reference depth is far beyond the depth of maximum dose, hence the $k_{Q, Qo}$ values would not be affected by the negligible absolute difference of 0.03 cm in reference depth due to the use of solid phantom. Practically also, $k_{Q, Qo}$ is a ratio of electrometer readings and will not be affected by a small systematic error in reference depth because the positioning would be affected in a similar way just like in the case of $TPR_{20,10}$. Moreover, being solid, the set depth would be constant for slab phantom during the measurements on both machines. Therefore, this difference in the reference depth as a result of using slab phantom instead of water was not included in the uncertainty budget [Table 4].

As plastic phantom takes more time to reach temperature equilibrium and the temperature gradient is also higher in comparison to the water phantom, the slabs were kept in treatment room 12 hrs before the measurement. This helped in attaining adequate temperature equilibrium of slabs with room air and also reduced uncertainty due to any possible temperature gradient in slab phantom. Further, to reduce type A uncertainty, five readings were taken for each measurement. All the measurements of linac were completed on the same day to avoid the probability of change in the beam quality. Furthermore, at least 5-min time was given for stabilization of dosimeter after changing polarizing potential or polarity to avoid any error in the measurements. Although the experiment was carried out on a single batch of slab phantom, the $k_{Qmsr}^{w, plastic}$ factor values used in the study were obtained from TRS-483 which indicates an average difference of 0.30% in $k_{Qmsr}^{w, plastic}$ factor values owing to the manufacturing variability of the solid water slab phantom and was therefore included as an uncertainty component in Table 4. TRS-398 reported uncertainty value for the cross-calibration step is 0.20% when a field ionization chamber is calibrated against reference ionization chamber. Since the same ionization chamber was used for both sets of measurements in this study, hence the related uncertainty was assessed to be not more than 0.10% for the cross-calibration step as given in Table 4 which is close to the reported uncertainty of a recent study.[19] The time required for the measurements in telecobalt machine is very small compared to the half-life (5.3 years) of ^{60}Co source and hence the relevant effect on output due to the decay of the source is negligible. On the other hand, the reported uncertainty value was used for the output stability of modern linac.[20]

For a given model of the chamber which is thought to be used for reference dosimetry, the $k_{Q, Qo}$ value of the chamber should ideally be generated and provided by the standards laboratory. MC method can also be used for generating this value, and once the value is verified as it has been the case for the values quoted in TRS-398, TG-51, or TRS-483, then only it can be used. However, if a new model of ionization chamber comes to a department and this chamber needs to be used for the reference dosimetry, then the user may use MC-calculated values as a temporary arrangement for using this chamber.

Conclusion

BQC factors were determined experimentally for six different ionization chambers. These data would be an addition to the group of BQC factors available in the literature and would be of use whenever the CoP will be updated[1,2] to recommend experimental BQC factors. Addendum to AAPM TG-51 report[4] also encourages the measurement of BQC factor via cross-calibration. More such data would be gathered from other investigators and more consistent BQC factors may be recommended in future. The experimentally measured values of BQC factor were different for different ionization chambers of the same make and model (inter-chamber variation). The magnitude of corresponding dose difference due to the difference between theoretical and experimentally measured values of BQC factor of the same make and model of the ionization chamber was up to 2.06% [Table 3]. Based on these observations, it is concluded that ionization chamber-specific BQC factor should be provided at the time of chamber calibration by the standards laboratory and be used to avoid any error in the estimation of absorbed dose to water that may be introduced due to ignoring inter-chamber variation in the response of ionization chamber.

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Conflicts of interest

There are no conflicts of interest.

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