Determination of consensus k_Q values for megavoltage photon beams for the update of IAEA TRS-398

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Abstract. The IAEA is currently coordinating a multi-year project to update the TRS-398 Code of Practice for the dosimetry of external beam radiotherapy based on standards of absorbed dose to water. One major aspect of the project is the determination of new beam quality correction factors, k_Q, for megavoltage photon beams consistent with developments in radiotherapy dosimetry and technology since the publication of TRS-398 in 2000. Specifically, all values must be based on, or consistent with, the key data of ICRU Report 90.

Data sets obtained from Monte Carlo (MC) calculations by advanced users and measurements at primary standards laboratories have been compiled for 23 cylindrical ionization chamber types, consisting of 725 MC-calculated and 179 experimental data points. These have been used to derive consensus k_Q values as a function of the beam quality index $\mathrm{TPR}_{20,10}$ with a combined standard uncertainty of 0.6%. Mean values of MC-derived chamber-specific f_{ch} factors for cylindrical and plane-parallel chamber types in ^{60}Co beams have also been obtained with an estimated uncertainty of 0.4%.

Keywords: TRS-398, MV photon beams, dosimetry, ionization chambers, Monte Carlo

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1. Introduction

The writing of the first edition of the IAEA TRS-398 Code of Practice (Andreo *et al.* 2000) for the dosimetry of external beam radiotherapy based on standards of absorbed dose to water was completed in the mid-1990s. A number of developments in radiotherapy techniques and dosimetry have taken place since that date, or will be implemented in the near future, which justify the need for updating the Code of Practice. Some of the more relevant aspects that require consideration in an update of TRS-398 are:

(i) New ionization chamber types have become commercially available that require beam quality correction factors, k_Q, for their use according to the recommendations of TRS-398. This requires an update of the list of ionization chamber types, some of them being already relatively old or even no longer available. Additionally, an extensive experimental study by McEwen (2010) revealed that not all chamber types originally listed in TRS-398 can be considered “reference class ionization chambers”.

(ii) The implementation of new radiotherapy technologies, mostly related to megavoltage (MV) photon beams, protons and heavier ions, whose reference dosimetry requires guidance and data for end users. There have been significant developments in linear accelerator technology and flattening-filter free (FFF) photon beams have become widely used. Their reference dosimetry (for 10 cm$\times$10 cm fields), described in the IAEA TRS-483 Code of Practice for small static fields, Palmans *et al.* (2017, 2018), needs to be taken into account while maintaining consistency with the recommendations of TRS-483.

(iii) The publication of ICRU Report 90 on Key Data for Ionizing-Radiation Dosimetry (Seltzer *et al.* 2016), recommending new values for the most relevant fundamental quantities and corrections. The impact of the new data on ionization chamber calibrations by standards laboratories and on beam quality correction factors for the different radiation modalities needs to be taken into account. Recent publications by Czarnecki *et al.* (2018), Mainegra-Hing and Muir (2018) and Pimpinella *et al.* (2019) on k_Q factors for MV photon beams have shown small differences between the use of ICRU Report 37 (Berger *et al.* 1984) and ICRU Report 90 data, but consistency throughout the dosimetry chain requires the use of the latter.

(iv) The Monte Carlo (MC) simulation of radiation transport has become a widely used technique for the accurate calculation of dosimetric quantities for all beam types, superseding many of the approximations used to determine the data in TRS-398.

(v) In the dosimetry of kilovoltage (kV) x rays, not only the previsions of TRS-398 for the ready availability of $N_{D,\mathrm{w}}$ calibrations for these beams have not become a reality, but also there were no specific data recommended to users. New data for the dosimetry of low- and medium-energy kV x rays using ICRU-90 data have been published (Andreo 2019).

An IAEA project was initiated to update TRS-398. A core working group was formed in 2016 with the task of re-writing relevant sections of text in TRS-398, coordinating the MC calculations and measurements at standards laboratories of beam quality correction factors made by different international research groups, and analysing their results to produce a consensus set of data for the different radiation modalities. For MV photon beams, one of the major objectives was to determine k_Q values averaged over data obtained by the research groups using different Monte Carlo codes and experimental data measured in laboratories having independent absorbed dose to water standards.

The purpose of this work is to summarize the methodology followed to derive consensus values of photon beam quality correction factors and their estimated uncertainty, to provide the parameters for a functional fit to the k_Q data available for a large number of ionization chamber types as a function of the photon beam quality index $\mathrm{TPR}_{20,10}$, and to make available tabulated values of k_Q. Mean values of Monte Carlo-derived $f_{\mathrm{ch}}(^{60}\mathrm{Co})$ chamber-specific factors for cylindrical and plane-parallel ionization chambers are also included. All the reported values are consistent with the key data given in ICRU Report 90 for graphite, water and air, whereas data from previous ICRU reports have been used for other materials.

2. Background

2.1. The k_{Q,Q_0} formalism

The beam quality correction factor, k_{Q,Q_0}, is defined in the formalism of IAEA TRS-398 as the ratio of the calibration coefficients of an ionization chamber in terms of absorbed dose to water at the beam qualities Q and Q_0:

$$k_{Q,Q_0} = \frac{N_{D,\mathrm{w},Q}}{N_{D,\mathrm{w},Q_0}}, \tag{1}$$

where Q_0 is the reference beam quality used by the standards laboratory. Values specifically measured for a particular user chamber should be used when available. In most cases, however, such data is not available and calculated k_{Q,Q_0} values must be used. In the current edition of TRS-398, for conditions where the Bragg–Gray cavity theory is applicable, values of k_{Q,Q_0} were calculated using the general expression (Andreo 1992):

$$k_{Q,Q_0} = \frac{(s_{\mathrm{w,air}})_Q}{(s_{\mathrm{w,air}})_{Q_0}} \frac{(p_{\mathrm{ch}})_Q}{(p_{\mathrm{ch}})_{Q_0}} \frac{(W_{\mathrm{air}})_Q}{(W_{\mathrm{air}})_{Q_0}}, \tag{2}$$

where $s_{\mathrm{w,air}}$ is the Spencer-Attix water-to-air stopping-power ratio, p_{ch} is the overall chamber perturbation correction factor, and W_{air} is the average energy to create an ion pair in dry air, all for the beam qualities Q and Q_0.

For MV photon beams, values of $s_{\mathrm{w,air}}$ were calculated using data from ICRU Report 37 (Berger *et al.* 1984) and the value of W_{air} was 33.97 eV for photons and electrons. Due to the lack of consistent data for the different components entering into the chamber perturbation correction factor p_{ch} (i.e., cavity perturbation, p_{cav}, displacement effect, p_{dis}, wall effect, p_{wall}, and central electrode correction, p_{cel}, see TRS-398), some values were derived from experiment, others by old MC or analytical calculations, and in some cases taken to be unity.

Since the publication of TRS-398, advanced MC techniques have been developed that enable the detailed simulation of ionization chambers and radiation sources (^{60}Co γ–ray units and clinical accelerators) with great efficiency. Rather than calculating independently $s_{\mathrm{w,air}}$

and chamber perturbation factor components for a given beam quality and ionization chamber, Sempau *et al.* (2004) proposed computing directly within the MC simulation the factor

$$f_{\rm ch}(Q) = \left[\frac{D_{\rm w}(P)}{\bar{D}_{\rm ch-air}}\right]_Q , \tag{3}$$

where $D_{\rm w}(P)$ is the dose to a point in water (in practice, calculated for a very small volume), and $\bar{D}_{\rm ch-air}$ is the mean absorbed dose in the chamber cavity. Note that no specific components of chamber perturbation correction factors are explicitly included in this factor and the constraint of small and independent components of $p_{\rm ch}$ required by cavity theory is no longer needed. The procedure in Eq. (3), which can be referred to as a *global* $f_{\rm ch}(Q)$ that includes $s_{\rm w,air}$ and all possible chamber perturbation components, irrespective of their size or interrelation (i.e., not being small and independent), has become the currently accepted MC calculation approach. It differs from the approach used by other authors, see, e.g., Paskalev *et al.* (2002) and Capote *et al.* (2004), where instead of the dose to a point, $D_{\rm w}(P)$, the dose to water is calculated in a volume identical to that of the chamber cavity, $D_{\rm w}(\rm vol)$. This alternative in fact leads to the calculation of the correction for the chamber volume averaging effect, $k_{\rm vol}$, and has been used in some of the MC data contributed to this work.

From Eqs. (2) and (3), the beam quality correction factor becomes defined as:

$$k_{Q,Q_0} = \frac{f_{\rm ch}(Q)}{f_{\rm ch}(Q_0)}\frac{(W_{\rm air})_Q}{(W_{\rm air})_{Q_0}}, \tag{4}$$

which using the reference quality Q_0 of ^{60}Co γ rays and noting the constancy of $W_{\rm air}$ for high-energy photons and electrons, yields

$$k_Q = \frac{f_{\rm ch}(Q)}{f_{\rm ch}(^{60}{\rm Co})}. \tag{5}$$

As opposed to the method for obtaining separately $s_{\rm w,air}$ and $p_{\rm ch}$ values, the approach to compute $f_{\rm ch}(Q)$, of which the product $(s_{\rm w,air}\, p_{\rm ch})_Q$ is an approximation, as a single quantity in a MC simulation has important advantages. In addition to both $f_{\rm ch}$ for k_Q in Eq. (5) being independent of the intrinsic approximations involved in cavity theory, the main advantage of an MC calculation of $f_{\rm ch}$ is that its uncertainty is considerably smaller than that resulting from combining the uncertainties of $s_{\rm w,air}$ and of $p_{\rm ch}$, where the values and their uncertainties are derived indirectly and independently.

There has been controversy on the constancy of $W_{\rm air}$ for high-energy radiotherapy beams since the mid 1980s. Should this quantity vary with energy, its influence would be intrinsically accounted for in k_Q measurements and, for consistency, MC calculations would need to be corrected for the variation. However, it should be emphasized that the ICRU Report 90 includes an in-depth review of the historical measurements and recent analysis made, concluding that $W_{\rm air}$ does not show a significant dependence with electron energy above a low-energy threshold (see figure 5.4 in ICRU-90), the spread of the data being consistent with the stated uncertainty of 0.12 eV (0.35%).

2.2. ICRU-90 key data

The ICRU Report 90 (Seltzer *et al.* 2016) on key data for measurement standards in radiation dosimetry has reviewed the quantities and correction factors that play a fundamental role in dosimetry, estimated the uncertainties of key data and analysed the implications of the new recommended data on measurements and calculations. The new key data has been endorsed by the CCRI (McEwen *et al.* 2017) and at its meeting in 2019 the National Metrology Institutes (NMIs) have committed to adopt ICRU-90 by the end of 2019 or by early 2020. Hence, the adoption of ICRU-90 data will be relatively rapid and comprehensive, and will in turn be implemented in standards laboratories for the calibration of ionization chambers.

ICRU-90 includes values of fundamental quantities entering into the determination of stopping powers for light- and heavy-charged particles. It provides recommendations for the mean excitation energy, the I-value, of air (85.7 eV), graphite (81 eV) and water (78 eV), and for the grain mass density of graphite to be used when evaluating the density effect (2.265 g cm^{-3}) in the mass electronic stopping power. These quantities yield new stopping power values for electrons and positrons, protons and light ions (alpha particles and carbon ions) and, indirectly, also change the average energy required to produce an ion pair for protons and carbon ions. The recommended values for $W_{\rm air}$ are 33.97 eV for electrons (which is constant above about 10 keV) and 34.44 eV for protons; for carbon ions the value is subject to the same increase as for protons (0.6 %, assuming negligible perturbation correction factors for the chambers used in its determination), i.e. the resulting $W_{\rm air}$ is estimated to be 34.71 eV.

The state of the art and current trends regarding photon cross sections and mass energy-absorption coefficient values and ratios are analysed in detail, but no specific data were recommended in ICRU-90 due to issues related to the photoelectric and Compton effects, where various options are available. Other key data, such as the heat defect of liquid water and the radiation chemical yield for the Fricke dosimeter, and the correction to account for the charge of the initial electrons set in motion by low-energy photons, have also been reviewed.

The impact of the new data on measurement standards, and therefore on ionization chamber calibrations by standards laboratories, varies depending on the radiation modality and type of standard used. The changes are up to about 0.8 % for air-kerma standards for kV x-ray and ^{60}Co beams (also for some brachytherapy sources, e.g. ^{192}Ir). A similar change could have been expected for the ionometric absorbed dose to water standard for ^{60}Co at the BIPM (reference for the IAEA Dosimetry Laboratory), but the implementation of the new data is assessed in the context of known changes to other correction factors resulting in a change of only 0.1 %. For graphite-calorimetry standards there are only small changes, mostly associated with the transfer methods used for converting dose in graphite to dose in water, which depends on the particular standard at each laboratory. No changes occur for water calorimetry.

3. Materials and methods

3.1. Determination of k_Q values

As already mentioned, k_Q values for MV photon beams were determined by different research groups worldwide, these being advanced MC users and standards laboratories, yielding comprehensive sets of new data for a large number of ionization chamber types. Details on the derivation of k_Q values by some of the research groups can be found in the Extended Synopses of the IAEA Symposium on "Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS 2019)" § and in recent and submitted publications by Czarnecki *et al.* (2018), Mainegra-Hing and Muir (2018), Pimpinella *et al.* (2019), Tikkanen *et al.* (2020), Giménez-Alventosa *et al.* (2020), etc.

Beam quality correction factors were determined by MC calculations according to Eq. (5), and by measurements at standards laboratories following Eq. (1). The beam qualities used were $\text{TPR}_{20,10}$ values between 0.6 and 0.8 approximately, 25 MeV being the highest energy; this range is considered to be representative of that widely used in the clinic.

For the experimental values, primary standards of absorbed dose to water based on water and graphite calorimetry were used; information on the standard used at each laboratory can be found in the on-line BIPM key comparison database (http://kcdb.bipm.org/) and the references therein. Waterproof sleeves generally of PMMA were used for chambers that are not waterproof, although the sleeve thickness varied for the different laboratories (typically not more than 1 mm). The stated standard uncertainties for the measured k_Q values were in the range from 0.3% to 0.5%.

The MC systems used were EGSnrc (Kawrakow *et al.* 2019a) and Penelope (Salvat 2014), usually in conjunction with the user codes *cavity* (Kawrakow *et al.* 2019b), *egs_chamber* (Wulff *et al.* 2008) and *penEasy* (Sempau *et al.* 2011). The MV radiation sources were phase–space files for different conventional (with flattening filter, WFF) and FFF linacs, and in some cases published spectra for several linacs (Mohan *et al.* 1985, Sheikh-Bagheri and Rogers 2002, Capote *et al.* 2006, Brualla *et al.* 2019). For ^{60}Co γ rays the most common source were spectra of therapy or laboratory units (Mora *et al.* (1999), Burns (2003)), although in some cases specific phase–space files for particular units were used. Details on the geometries of the individual ionization chamber types were in most cases provided by the respective manufacturers. In all cases the MC groups obtained k_Q values with Type A standard uncertainties of the order of 0.15%.

To verify the homogeneity of the MC calculations, all the groups were requested to calculate k_Q values for a NE-2571 Farmer-type ionization chamber in photon beams of different qualities. For this purpose, a detailed NE report was distributed to the groups (Nuclear Enterprises 1984) to minimize the influence of using different geometry descriptions. The goal was to establish the degree of variation of the k_Q values when implementing a common chamber geometry as a result of the different MC transport parameters and codes used by each group.

§ https://www.iaea.org/sites/default/files/19/06/cn-273-book-extended-synopses.pdf

For the reference dosimetry of FFF beams the update of TRS-398 will introduce an additional chamber-reading correction $k_{\rm vol}$ to account for the volume averaging effect whenever the beam profile across the detector is not homogeneous, a correction discussed in detail in TRS-483. This choice has been preferred over the alternative of providing different k_Q values for FFF and WFF photon beams, as is done in TRS-483. Special linacs such as CyberKnife, MR-linacs etc, have not been included in the compilation of data because either their use is rather limited or those delivering small fields are already considered in TRS-483. Note also that the current edition of TRS-398 includes recommendations for the dosimetry of radiotherapy beams in non-standard conditions, i.e., for beam dimensions different from the 10 cm$\times$10 cm reference field size. The update will maintain the recommendations and include new developments, particularly for the dosimetry of small MV fields in TRS-483, providing a consistent framework for these conditions.

Equation (5) shows that all calculations require $f(Q_0)$ data for the reference quality of ^{60}Co γ rays, which were provided separately by some of the groups; the goal was to produce a harmonized common data set to be used with other radiation modalities also based on ^{60}Co as the reference quality (electrons, protons and heavier ions).

3.2. Analysis of the data

A total of 725 MC-calculated and 179 measured data points were compiled for the 23 cylindrical chamber types analysed, see Table 1. The two sets of beam quality factors for each chamber type were combined to obtain statistically-based consensus k_Q values and their uncertainty estimates, the latter referring to the relative standard uncertainty ($k = 1$) expressed as a percentage.

For each chamber type, the combined data set of MC and experimental values was fitted using a module developed with version 10 of *Mathematica* (Wolfram Research Inc. 2016), having the empirical functional form

$$k_Q(\mathrm{TPR}_{20,10}) = \frac{1+\exp\left(\dfrac{a-0.57}{b}\right)}{1+\exp\left(\dfrac{a-\mathrm{TPR}_{20,10}}{b}\right)}, \tag{6}$$

where a and b are specific parameters for each chamber type, and the nominal value 0.57 is taken to represent the $\mathrm{TPR}_{20,10}$ value typically measured for a ^{60}Co γ-ray unit (forcing $k_Q = 1$ for this reference quality). This value is included in the figures below, but it should be noted that considering the $\mathrm{TPR}_{20,10}$ of ^{60}Co γ-ray beams in parallel with values for MV photon beams is a convenient but not rigorous approach, as the photon spectra from a radionuclide and from bremsstrahlung are substantially different.

The sensitivity of the k_Q fits to the $\mathrm{TPR}_{20,10}(^{60}\mathrm{Co})$ value used was tested for the five chambers having the largest number of data points (see Figs. 1 and 2) using the lowest (0.568) and highest (0.578) values found in the literature for $\mathrm{TPR}_{20,10}(^{60}\mathrm{Co})$. As the lowest value is very close to the nominal value 0.57 used for the fits, the analysis was focused on the upper limit, obtained from the BJR-25 data (Aird *et al.* 1996). For MV beams having $\mathrm{TPR}_{20,10} = 0.6$, which is approximately the lowest beam quality used in the MC and experimental k_Q determinations, the maximum difference in the fitted k_Q value using the nominal and the highest $\mathrm{TPR}_{20,10}(^{60}\mathrm{Co})$ was 0.05%, being below this difference for $\mathrm{TPR}_{20,10} > 0.6$. The influence of the $\mathrm{TPR}_{20,10}(^{60}\mathrm{Co})$ value used in the k_Q fits was therefore considered to be negligible.

The parameters a and b of the best k_Q fit to the combined MC and measured data sets were determined for each chamber type. The standard deviation of the experimental data with respect to the combined fit was corrected statistically (see Section 5) and taken as the standard uncertainty of the fit for each chamber type. The mean value for all the chamber types contributed to the overall standard uncertainty estimation. Prediction limits of the fits at the 95% level were also determined and plotted in the figures (note that these do not represent the prediction limits for the consensus k_Q values given in this report; the k_Q uncertainties are discussed in Section 5).

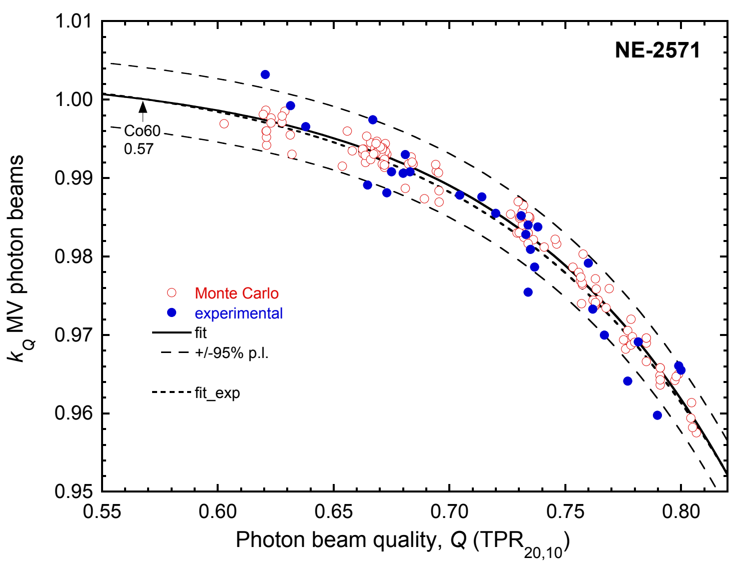

Figure 1: *Values of k_Q for megavoltage photon beams obtained from Monte Carlo calculations by different research groups (open circles) and measured at standards laboratories (filled circles) for a NE-2571 Farmer-type ionization chamber. The solid line is a fit to the total of 154 data points using Eq. (6) and the dashed lines are the 95% prediction limits of the fit. The short-dashed line corresponds to the fit of the 28 experimental data points.*

4. Results and discussion

4.1. High-energy photon beams

The k_Q results obtained for the NE-2571 Farmer-type chamber are shown in Fig. 1, which includes a fit to the combined 126 MC-calculated and 28 measured data points, yielding a root mean square (rms) difference of the data about the fit of 0.2%. It can be seen that most results agree within about $\pm 0.5\%$, showing consistency in the different determinations for this common chamber type. The differences in the MC-calculated k_Q factors for this chamber type were not significant, indicating no systematic dependence on the particular MC system (EGSnrc versus PENELOPE) or specific user code parameters. The figure includes a fit to the measured data alone, which practically coincides with the combined fit. Also shown are the 95% prediction limits for the combined fit, which for this chamber type with a relatively large data set are significantly narrower than those arising from the uncertainties for the consensus k_Q values discussed in Section 5, which are based on the deviations of the experimental data from the combined fit. Observe also that some experimental data points at $\mathrm{TPR}_{20,10}$ values greater than about 0.73 appear slightly below the -95% prediction limits, a trend that appears also in the fits for other chamber types and remains to be explained.

As mentioned above, k_Q data were supplied by different contributors and standards laboratories. Many of the k_Q measurements and MC simulations were carried out within the EURAMET 16NRM03 RTNORM project (Pinto 2019); other significant data sets were the comprehensive experimental set of McEwen (2010) and MC data by the NRCC group (Muir and Rogers 2010, Muir *et al.* 2011, Mainegra-Hing and Muir 2018). On the other hand, the extensive set of k_Q measurements by Seuntjens *et al.* (2000) have not been included in the compilation because the NRC beams used at that time, generated with aluminium targets and filters combined with magnetic sweeping for flattening, had substantially different spectral characteristics compared with those of current clinical linac beams.

For the MC-calculated and experimental k_Q data sets, consensus values were determined for 23 ionization chamber types and different beam qualities. It should be noted that some of these chamber types (Exradin A28, PTW 31021) have not yet been shown to be reference-class according to the criteria by McEwen (2010) and one chamber type (PTW 31016) has been shown to not exhibit reference-class behaviour. Table 1 shows the chamber types and number of MC-derived and experimental k_Q determinations. Values of the chamber-type specific parameters a and b obtained from the combined fit using Eq. (6) for the different chamber types are included in the table. The rms difference of the data about the fits varied between 0.05% and 0.4%, yielding an average of 0.23%.

Regarding FFF beams and the effect of volume averaging on chamber response, it should be noted that all experimental determinations entering into k_Q are corrected for volume averaging (either explicitly or implicitly). Hence, ignoring possible spectral differences, an FFF beam and a WFF beam of the same $\mathrm{TPR}_{20,10}$ should have approximately the same experimental value for k_Q. This assertion has been verified experimentally by e.g. De Prez *et al.* (2018), finding differences of less than 0.23% (uncertainty smaller than 0.35%) for eight Farmer-type ion chambers of three different models in 6 MV and 10 MV paired WFF and FFF beams having the same $\mathrm{TPR}_{20,10}$ in each case. In contrast, the MC calculations for FFF beams have taken different approaches such that volume averaging is not always treated in the same way. Furthermore, different input spectra have been used, some derived from full phase-space calculations and others using a simplified source that might not contain realistic beam profile information. Despite these differences, the scatter of the combined MC results for FFF and WFF beams does not show any significant effect arising from this heterogeneous treatment

Table 1: *Chamber types and number of Monte Carlo-derived and experimental k_Q determinations for high-energy photon beams of different qualities. The two rightmost columns correspond to the values of the chamber-type specific parameters a and b obtained from the different fits using Eq. (6).*

Ionization chamber type	Number of data points		Chamber-type specific parameters	
	Monte Carlo	experimental	a	b
Capintec PR-06C Farmer	10	3	1.06833	-0.08262
Exradin A1SL Miniature Shonka	14	6	1.21633	-0.13351
Exradin A12 Farmer	35	6	1.09783	-0.09544
Exradin A12S Farmer	16	3	1.11499	-0.10057
Exradin A18	10	3	1.10487	-0.09670
Exradin A19 Classic Farmer	29	6	1.12024	-0.10493
Exradin A26	10	3	1.09587	-0.09383
Exradin A28	19	3	1.12453	-0.10278
IBA CC13	42	6	1.11441	-0.10260
IBA CC25	10	3	1.08981	-0.09254
IBA FC23-C Short Farmer	19	3	1.09189	-0.09346
IBA FC65-G Farmer	64	20	1.09752	-0.09642
IBA FC65-P Farmer	42	3	1.12374	-0.10784
NE 2561/2611A Secondary Standard	20	19	1.07699	-0.08732
NE 2571 Farmer	126	28	1.08918	-0.09222
PTW 30010 Farmer	25	3	1.12594	-0.10740
PTW 30011 Farmer	15	0	1.10850	-0.10107
PTW 30012 Farmer	25	13	1.12442	-0.10415
PTW 30013 Farmer	65	23	1.18273	-0.13256
PTW 31010 Semiflex	29	6	1.23755	-0.15295
PTW 31013 Semiflex	48	6	1.19297	-0.13366
PTW 31016 PinPoint	15	0	1.11650	-0.10841
PTW 31021 Semiflex 3D	37	13	1.29612	-0.16514
Total number of determinations	725	179		

of volume averaging, being consistent with the estimated uncertainties of this work. This agrees with the findings of recent publications (Lye *et al.* 2016, Czarnecki *et al.* 2018). It can therefore be concluded that the consensus k_Q values provided in this work, obtained by combining experimental and MC results, can be used equally for WFF and FFF beams having the same $\mathrm{TPR}_{20,10}$ without significant additional uncertainty. Users of FFF beams should, on the other hand, correct their dosimeter readings by a volume averaging correction, k_{vol}, which parallels the procedure used for chamber calibration at standards laboratories.

Examples of k_Q data and their fits for some of the ionization chamber types commonly used, namely the Farmer-types IBA FC65-G, PTW 30013 and Exradin A12, and the PTW 31013 Semiflex, are shown in Fig. 2. As for the NE-2571 chamber type, some experimental data fall slightly below the -95% prediction limits of the overall fit.

Beam quality correction factors are given in Table 2 for different $\mathrm{TPR}_{20,10}$ values. They have been calculated with Eq. (6) using the chamber-type specific parameters a and b given in Table 1. It is emphasized that the k_Q values provided here do not distinguish possible chamber-to-chamber variations of a given chamber type (see, e.g., Andreo *et al.* (2013))

and their use does not preclude the possibility that an individual chamber deviates from the expected behaviour, leading to a source of error that is circumvented when the values are measured at a standards laboratory for a specific user chamber. For waterproof chambers, the k_Q values provided assume that no waterproof sleeve is used. The use of a PMMA sleeve 1 mm in thickness increases the k_Q value by up to 0.3% at the highest energies. For non-waterproof chambers, the k_Q values provided are appropriate for a 1 mm PMMA sleeve.

4.2. ^{60}Co gamma radiation

All the k_Q values in TRS-398 and in the present work are based on the reference quality of ^{60}Co γ rays. For the MC calculations associated with the present work, the global factor $f_{\rm ch}(^{60}{\rm Co})$, see Eq. (5), was determined for each chamber type.

As emphasized in Section 2.1, the approach to compute $f_{\rm ch}(^{60}{\rm Co})$ as a single quantity in a MC simulation, as opposed to obtaining separately $s_{\rm w,air}$ and $p_{\rm ch}$ values, has the advantage of a smaller uncertainty than that resulting from combining the uncertainties of $s_{\rm w,air}$ and of $p_{\rm ch}$ from different sources. Therefore, whereas the use of specific $s_{\rm w,air}$ and $p_{\rm ch}$ values is acceptable for proton and heavier ions due to the lack of comprehensive sets of chamber–specific MC-derived $f_{\rm ch}(Q)$ values, for the ^{60}Co data in the denominator of k_Q the use of $f_{\rm ch}(^{60}{\rm Co})$ is preferred as it provides consistency among the high-energy radiation modalities included in TRS-398.

Mean values of MC-calculated $f_{\rm ch}(^{60}{\rm Co})$ factors were obtained from 16 data sets (115 data points for the cylindrical chambers in this work as well as nine plane-parallel chambers) extracted from publications and data supplied by different research groups. They are given in Table 3 for the different chamber types, for which an average standard uncertainty estimate of 0.4% was obtained. These $f_{\rm ch}(^{60}{\rm Co})$ chamber-type specific values are intended to replace the $(s_{\rm w,air}\, p_{\rm ch})_{^{60}{\rm Co}}$ data given in Table 37 of the first edition of TRS-398.

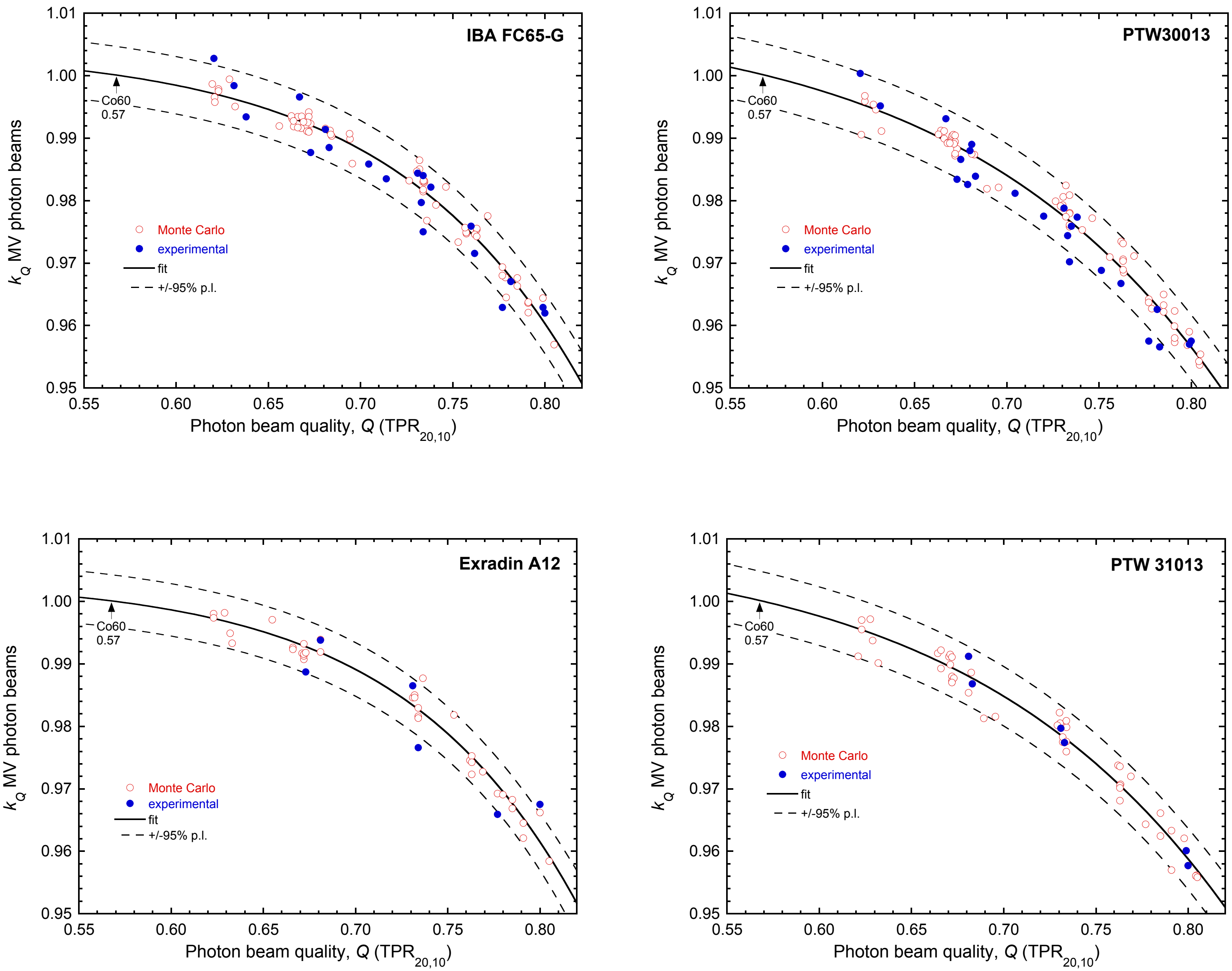

Figure 2: *Values of k_Q for megavoltage photon beams obtained from Monte Carlo calculations by different research groups (open circles) and measured at primary laboratories (filled circles) for the Farmer-type chambers IBA FC65-G, PTW 30013 and Exradin A12, and the PTW 31013 Semiflex chamber type. The solid lines are fits to the combined data set using Eq. (6) and the dashed lines are the 95% prediction limits of the fit.*

Table 2: *Calculated values of beam quality correction factors, k_Q, as a function of the beam quality index $TPR_{20,10}$ of megavoltage photon beams, derived with Eq. (6) using the chamber-type specific parameters a and b given in Table 1.*

Chamber type	0.50	0.53	0.56	0.59	0.62	0.65	0.68	0.70	0.72	0.74	0.76	0.78	0.80	0.82
Capintec PR-06C Farmer	1.0014	1.0009	1.0003	0.9993	0.9980	0.9961	0.9934	0.9909	0.9878	0.9839	0.9790	0.9727	0.9649	0.9551
Exradin A1SL Miniature Shonka	1.0032	1.0020	1.0006	0.9987	0.9965	0.9936	0.9901	0.9873	0.9840	0.9802	0.9759	0.9709	0.9652	0.9586
Exradin A12 Farmer	1.0021	1.0014	1.0004	0.9991	0.9973	0.9948	0.9915	0.9887	0.9852	0.9809	0.9756	0.9693	0.9615	0.9521
Exradin A12S Farmer	1.0022	1.0014	1.0004	0.9990	0.9972	0.9947	0.9913	0.9885	0.9850	0.9809	0.9758	0.9698	0.9624	0.9537
Exradin A18	1.0020	1.0013	1.0004	0.9991	0.9973	0.9949	0.9917	0.9889	0.9855	0.9814	0.9764	0.9702	0.9628	0.9538
Exradin A19 Classic Farmer	1.0026	1.0017	1.0005	0.9989	0.9968	0.9940	0.9904	0.9873	0.9836	0.9792	0.9738	0.9675	0.9599	0.9509
Exradin A26	1.0019	1.0013	1.0004	0.9991	0.9974	0.9951	0.9919	0.9891	0.9857	0.9816	0.9765	0.9702	0.9626	0.9533
Exradin A28	1.0022	1.0015	1.0004	0.9990	0.9972	0.9947	0.9914	0.9886	0.9853	0.9813	0.9764	0.9706	0.9636	0.9552
IBA CC13	1.0024	1.0016	1.0005	0.9989	0.9969	0.9942	0.9906	0.9876	0.9839	0.9795	0.9742	0.9678	0.9601	0.9510
IBA CC25	1.0019	1.0013	1.0004	0.9991	0.9974	0.9950	0.9918	0.9890	0.9855	0.9812	0.9760	0.9695	0.9617	0.9521
IBA FC23-C Short Farmer	1.0020	1.0013	1.0004	0.9991	0.9974	0.9950	0.9917	0.9888	0.9853	0.9810	0.9758	0.9693	0.9614	0.9519
IBA FC65-G Farmer	1.0022	1.0014	1.0004	0.9990	0.9972	0.9946	0.9912	0.9882	0.9846	0.9802	0.9748	0.9683	0.9603	0.9507
IBA FC65-P Farmer	1.0028	1.0018	1.0005	0.9988	0.9966	0.9936	0.9897	0.9865	0.9826	0.9780	0.9725	0.9660	0.9583	0.9491
NE 2561/2611A Secondary Standard	1.0017	1.0011	1.0003	0.9992	0.9977	0.9955	0.9925	0.9898	0.9865	0.9823	0.9771	0.9706	0.9627	0.9528
NE 2571 Farmer	1.0019	1.0013	1.0004	0.9991	0.9974	0.9951	0.9919	0.9891	0.9856	0.9813	0.9761	0.9697	0.9618	0.9522
PTW 30010 Farmer	1.0027	1.0017	1.0005	0.9989	0.9967	0.9938	0.9901	0.9869	0.9832	0.9787	0.9734	0.9671	0.9595	0.9506
PTW 30011 Farmer	1.0024	1.0016	1.0005	0.9989	0.9969	0.9942	0.9906	0.9875	0.9838	0.9793	0.9739	0.9674	0.9595	0.9501
PTW 30012 Farmer	1.0024	1.0016	1.0004	0.9990	0.9970	0.9944	0.9910	0.9881	0.9846	0.9804	0.9754	0.9694	0.9622	0.9536
PTW 30013 Farmer	1.0040	1.0025	1.0007	0.9984	0.9956	0.9920	0.9876	0.9840	0.9800	0.9753	0.9699	0.9636	0.9565	0.9484
PTW 31010 Semiflex	1.0046	1.0029	1.0008	0.9982	0.9952	0.9914	0.9869	0.9835	0.9795	0.9750	0.9700	0.9643	0.9579	0.9507
PTW 31013 Semiflex	1.0038	1.0024	1.0007	0.9985	0.9958	0.9924	0.9882	0.9848	0.9810	0.9765	0.9714	0.9655	0.9588	0.9511
PTW 31016 PinPoint	1.0031	1.0020	1.0006	0.9987	0.9962	0.9930	0.9888	0.9853	0.9812	0.9762	0.9703	0.9632	0.9549	0.9451
PTW 31021 Semiflex 3D	1.0042	1.0026	1.0007	0.9984	0.9957	0.9925	0.9886	0.9856	0.9823	0.9786	0.9744	0.9697	0.9645	0.9587

Table 3: *Mean values of Monte Carlo-derived $f_{\rm ch}(Q_0)$ chamber-specific factors, approximately equal to the product $s_{\rm w,air}\, p_{\rm ch}$ for ^{60}Co γ-ray beams. The values were obtained averaging the contribution by different MC groups, yielding an overall standard uncertainty estimate of 0.4%.*

Ionization chamber type	$f_{\rm ch}(^{60}{\rm Co})$
Cylindrical chambers	
Capintec PR-06C Farmer	1.1045
Exradin A1SL Miniature Shonka	1.1030
Exradin A12 Farmer	1.1064
Exradin A12S Farmer	1.1046
Exradin A18	1.1023
Exradin A19 Classic Farmer	1.1074
Exradin A28	1.1095
IBA CC13	1.1098
IBA CC25	1.1039
IBA FC23-C Short Farmer	1.1077
IBA FC65-G Farmer	1.1081
IBA FC65-P Farmer	1.1135
NE 2561/2611A Secondary Standard	1.1062
NE 2571 Farmer	1.1084
PTW 30010 Farmer	1.1072
PTW 30011 Farmer	1.1129
PTW 30012 Farmer	1.1000
PTW 30013 Farmer	1.1086
PTW 31010 Semiflex	1.1074
PTW 31013 Semiflex	1.1110
PTW 31016	1.1260
PTW 31021 Semiflex 3D	1.0951
Plane-parallel chambers	
Exradin A10	1.1137
Exradin A11	1.1115
Exradin A11TW	1.0994
IBA NACP-02	1.1535
IBA PPC-05	1.1409
IBA PPC-40	1.1424
PTW Adv. Markus	1.1434
PTW Markus	1.1428
PTW Roos	1.1417

5. Estimation of uncertainties of the k_Q data

The statistical analysis of the k_Q values obtained for different ionization chamber types was similar to the procedure used in IAEA TRS-483; it included all the available data sets determined by the various MC and experimental groups. For each chamber type an initial fit was made to the combined data set using Eq. (6); data points outside the 99.73% ($k = 3$) prediction limits of the fit were filtered out and the fit repeated. Considering that most determinations stated similar relative uncertainties and that these were of different type (combined uncertainties for measured data, Type A uncertainties only for MC data), the various input data sets were not weighted statistically.

The estimation of uncertainties of the k_Q values was done as follows:

(i) The MC calculations do not include estimates of Type B uncertainties, and the calculated k_Q data provided by the different research groups is expected to have correlated uncertainties that do not appear as scatter in their values, which were obtained with the same or similar MC systems.

It should be emphasized that the estimation of Type B uncertainties in MC calculations involves considerable difficulty. Although some authors have estimated Type B uncertainties of 0.2% – 0.4% for MV photon beams (Wulff *et al.* 2010, Muir and Rogers 2010), their analysis did not account for components due to the single and multiple electron scattering theories and their implementation in the MC system used, which for years have been considered a major constraint for the MC simulation of ionization chambers (see, e.g., Berger and Wang (1988), Bielajew and Rogers (1988) and Andreo *et al.* (2017)). This constraint also includes the boundary crossing algorithms and the condensed-history step mechanics, which are linked to the implementation of the scattering theories but usually are controlled separately in a MC simulation.

(ii) In contrast, the experimental data for k_Q provided by different laboratories are largely uncorrelated and deviations from the combined fit evaluated for these data alone provide a more robust basis for an uncertainty estimate. For each chamber type the relative deviation from the fit increased slightly with $\text{TPR}_{20,10}$, but the change was small enough to justify adopting an overall quality–independent uncertainty. Fits made for the different chamber types yielded on average a standard prediction uncertainty of 0.51% (reducing to 0.36% when considering only the five chamber types with the most experimental data). This estimate involves (a) the rms deviation s_{rms} of the measured data with respect to the combined fit, (b) the standard uncertainty s including Student's t correction $s = s_{\text{rms}}\, t_{1-0.68,n-1}$, as only five chamber types had a large number n of measured data points, and (c) the standard prediction uncertainty using $s_{\text{p}} = s\,\sqrt{1+1/n}$.

(iii) A contribution was also included for the experimental uncertainty. The rationale for this estimate was that approximately half of the chamber types have only three measured data points, corresponding to one individual chamber measured at one laboratory (three energies), and consequently these data contain no scatter due to the laboratory uncertainties or chamber-to-chamber variations. For each of these chamber types the additional contribution was derived as the mean value of s (as in the previous step) for the five chamber types having most measured data points. This mean value of 0.34% is consistent with the range of standard experimental uncertainties for k_Q stated by the laboratories. A further seven chamber types have data for only two individual chambers, for which a corresponding contribution of $0.34\,\sqrt{1/2} = 0.24\%$ was included. The net effect of these additions on the total uncertainty is 0.28%, as indicated in Table 4.

(iv) Finally, the uncertainty of assigning k_Q values to a given photon beam quality was estimated to be 0.2%. This includes uncertainty components for the use of phase-space data files or photon spectra in MC calculations and for any difference in the measurement of $TPR_{20,10}$ between the research groups providing the data and the end user (for both WFF and FFF beams).

The different components are summarized in Table 4, yielding a combined standard uncertainty for the k_Q values of high-energy photons obtained in this work of about 0.6%. This uncertainty can be considered a conservative estimate for any of the chamber types listed in Table 1. However, as noted in point (ii) above, for the five chamber types with the most data the prediction uncertainty is significantly smaller, leading to an overall uncertainty for k_Q approaching 0.4% when these chamber types are used. The uncertainty of 0.6% does not preclude a future reduction in uncertainty for any chamber type for which significant data becomes available.

Table 4: *Estimated relative standard uncertainty of the k_Q values for megavoltage photon beams.*

Component	u_c (%)
Prediction uncertainty from fit using Eq. (6)	0.51
Net experimental uncertainty	0.28
Assignment of k_Q to $TPR_{20,10}$	0.20
Combined standard uncertainty in k_Q	0.62

6. Summary and conclusions

Beam quality correction factors, k_Q, for the dosimetry of megavoltage photon beams, contributed by international research groups for the update of the IAEA TRS-398 Code of Practice, have been compiled. The data have been calculated by advanced Monte Carlo users and measured by standards laboratories for 23 ionization chamber types, yielding a total of 725 MC-calculated and 179 experimental data points. This work describes the methods followed to derive consensus k_Q values, providing fitting parameters and tabulated data for each chamber type as a function of the $TPR_{20,10}$ photon beam quality index. Mean values of MC-derived chamber-specific factors for cylindrical and plane-parallel ionization chambers in ^{60}Co γ-ray beams are also given. All the values provided are based on, or are consistent with, the key data of ICRU Report 90.

The analysis of the k_Q data yields, on average, rms differences between the input data and the fitted values of the order of 0.2%. There is good data integrity, as all the input data agree with the fits approximately at the 0.5% level; however, some experimental data points at $TPR_{20,10}$ greater than about 0.73 fall slightly below the -95% prediction limit, a trend that appears to be systematic, rather than random, and that requires further investigation. The combined standard uncertainty of the consensus k_Q values is estimated to be 0.6%. It is concluded that the consensus k_Q values provided in this work can be used equally for WFF and FFF beams having the same $TPR_{20,10}$ without significant additional uncertainty.

The updated data sets are expected to contribute to the harmonization and accuracy of radiotherapy beam calibrations based on a systematic and internationally unified approach.

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