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Monte Carlo calculations and measurements of beam quality correction factors for the PTW PinPoint 3D chamber type 31022 in megavoltage photon beams

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Abstract

The aim of the presented work was to calculate beam quality correction factors (k_Q) in megavoltage photon beams for the PTW PinPoint 3D type 31022 chamber, to be included in the forthcoming update of the IAEA TRS-398 Code of Practice. The methodology of this work followed that in the consensus k_Q data for other ionization chambers published by Andreo *et al.* (2020). Three independent groups have performed Monte Carlo calculations of k_Q, one group using the PENELOPE system and two groups using EGSnrc. One further group at the National Metrology Institute of Germany (PTB) has performed k_Q measurements in an Elekta Precise linac. The work was initiated with Monte Carlo calculations for the NE 2571 chamber to verify the consistency with the consensus k_Q values for this chamber, finding good agreement. The data of the four groups for the PinPoint 3D type 31022 chamber showed good consistency and the statistical analysis yielded the values 1.14435 and -0.111303 for the parameters a and b of Eq. (6) in Andreo *et al.* (2020).

Contents

1. Introduction

In 2020 a paper was published (Andreo *et al.* 2020) containing ionization chamber consensus data for the beam quality factors in megavoltage photon beams obtained from Monte Carlo calculations by different groups and measurements at standards dosimetry laboratories. The purpose of the consensus k_Q values was to harmonize the data to be included in the forthcoming update of the IAEA TRS-398 Code of Practice. This publication included data for the former PTW PinPoint 3D chamber, the type 31016, but this chamber is now discontinued and no longer in sale.

To include the PinPoint 3D successor model, type 31022, into the TRS-398 update, a project was undertaken following the methodology in Andreo *et al.* (2020), where Monte Carlo calculations and measurements of k_Q for this chamber type were performed by several groups. The combined data sets were analyzed statistically, yielding consensus data for this chamber type. Monte Carlo calculations were performed by the group of Prof. Javier Vijande (henceforth termed "Valencia"), Dr. Hui Khee Looe (henceforth termed "Oldenburg") and Prof. Klemens Zink (henceforth termed "Giessen"). Measurements were performed by the team of Dr. Ralf-Peter Kapsch from the German metrology institute PTB (termed "Braunschweig" in what follows). The project was steered by Prof. Pedro Andreo. For affiliation details of the scientists involved see the authors list of the report.

The present publication provides information on how the k_Q values were derived by the different groups and on the statistical analysis performed to arrive at consensus values for the PTW PinPoint 3D chamber, type 31022.

2. Materials and methods

In general, the methodology described in Andreo *et al.* (2020) was followed for the Monte Carlo calculations and for the statistical analysis of their data, which combined the results of the calculations with the experimental determinations.

2.1. The chamber

The PinPoint 3D, type 31022 (PTW-Freiburg, Freiburg, Germany) is a waterproof vented air-filled ionization chamber with a cavity radius of 1.45 mm and a cavity length of 2.9 mm, see Fig 1. The central electrode is made of aluminium and the wall of graphite and PMMA. The chamber is to be used at the nominal voltage of 300 V.

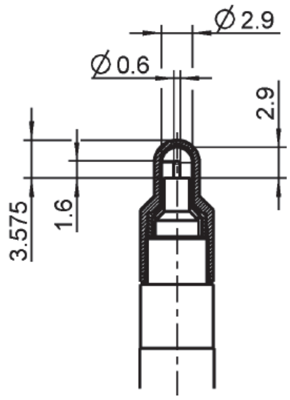

Figure 1. Diagram of the PinPoint 3D, type 31022 ionization chamber taken from the manual of the detector. The dimensions provided are in millimetres.

2.2. Monte Carlo calculations

Monte Carlo calculations of beam quality factors k_Q rely on the definition (Sempau *et al.* 2004)

$$k_Q = \frac{f_{\text{ch}}(Q)}{f_{\text{ch}}(^{60}\text{Co})} = \frac{\left[D_{\text{w}} / \overline{D}_{\text{ch-air}}\right]_Q}{\left[D_{\text{w}} / \overline{D}_{\text{ch-air}}\right]_{^{60}\text{Co}}} \tag{1}$$

where D_{w} and $\overline{D}_{\text{ch-air}}$ are the calculated dose to a point in water (in practice, a very small volume) and the mean absorbed dose in the chamber air cavity, respectively, calculated for the beam quality Q and for the ^{60}Co reference quality. Hence, each beam quality factor involves the calculation of four quantities. The symbols $f_{\text{ch}}(Q)$ and $f_{\text{ch}}(^{60}\text{Co})$ approximate the product $s_{\text{w,air}}\, p_{\text{ch}}$ in the analytical calculations of k_Q in IAEA TRS-398 (Andreo *et al.* 2000), $s_{\text{w,air}}$ being the water/air stopping-power ratio and p_{ch} the overall chamber perturbation factor.

As in the k_Q consensus paper (Andreo *et al.* 2020), beam quality factors were calculated for the PinPoint 3D type 31022 and for the NE 2571 ionization chambers for a range of megavoltage beam qualities. The latter data sets were taken as a reference to verify the homogeneity of the calculations and establish the degree of variation of the k_Q values when implementing the chamber geometry and diverse transport parameters in the simulations. The resulting data for the NE 2571 chamber type were compared with those in the k_Q consensus paper.

The Valencia calculations were made with the PENELOPE 2014 system (Salvat 2015) using the penEasy user code (Sempau *et al* 2011). Calculations by the Giessen and Oldenburg groups were performed with the EGSnrc system (Kawrakow *et al.* 2017) using the egs_chamber code (Wulff *et al.* 2008). All the Monte Carlo codes have passed the Fano cavity test with 0.1% accuracy and their suitability for the simulation of ionization chambers has been widely demonstrated by e.g. Sempau and Andreo (2006) for PENELOPE and by Kawrakow (2000) and Czarnecki *et al.* (2018) for EGSnrc. The three groups perform their calculations using stopping powers for water, graphite and air from ICRU Report 90 (Seltzer *et al.* 2016); for aluminium and PMMA they were from ICRU Report 37 (Berger *et al.* 1984). Other key data used have been described in Czarnecki *et al.* (2018), Giménez-Alventosa *et al.* (2020) and Kretschmer *et al.* (2020) for k_Q calculations for other chambers by the present authors. The number of simulated histories was in the range 10^{10} to 10^{12}, depending on the spectra considered, to achieve Type A uncertainties below 0.1%.

The geometry configuration followed the recommendations by TRS-398 for the calibration of megavoltage photon beams using either an isocentric set up by the Valencia group, i.e., a constant source-to-isocenter distance, or a constant source-to-surface distance (SSD) by the Giessen and Oldenburg groups. A divergent 10 cm ×10 cm photon beam, with the field size defined at the isocenter or at the SSD, irradiated a 30 cm × 30 cm × 30 cm water phantom. The Valencia calculation depth was 10 cm using a source-to-chamber distance (SCD) of 100 cm both for the beam quality Q and for the

^{60}Co reference quality, hence the SSD was 90 cm. For the Giessen and Oldenburg groups the calculation depths were 10 cm for the megavoltage beams and 5 cm for ^{60}Co, both with an SSD of 100 cm (SCD of 110 cm). The 10 cm calculation depth was taken to be the distance from the phantom surface to the reference point of the chamber, located on the central axis of the active air volume. Referring to Eq. (1), the absorbed dose to a point in water D_{w} was calculated as the dose to water in a cylindrical voxel of 1 cm radius and 0.025 cm height with its centre positioned at the 10 cm calculation depth.

For the Valencia group, the MV radiation sources were the classical spectra from Mohan *et al* (1985) and the ^{60}Co spectrum from the Bureau International des Poids et Measures (BIPM) described by Burns (2003), both types assumed to be point sources spectra. Within the water voxel for the calculation of D_{w} all electrons and photons were transported down to a kinetic energy of 1 keV; the same photon energy cut-off was used in the voxel and elsewhere. Outside the voxel, the electron transport cut-off was 200 keV, justified in terms of the electron csda range (<0.05 cm) and the radiation yield in water being less than 0.1%, consistent with the accuracy goal. The mean absorbed dose to air in the ionization chamber cavity $\overline{D}_{\text{ch-air}}$ was calculated surrounding the chamber with a water shell 0.05 cm thick. Within this composite volume, the transport of electrons and photons was simulated down to an energy of 1 keV in a collision-by-collision mode. Outside this volume, an energy cut-off of 200 keV was set for the electrons, whose transport was simulated using the conventional condensed-history mode. This procedure ensured that electrons produced in the water shell were able to reach the chamber, whereas those generated outside the shell were absorbed before reaching the chamber.

For the Oldenburg calculations the MV radiation sources were the spectra from Mohan *et al* (1985) and the ^{60}Co spectrum from Mora *et al.* (1999), both types assumed to be point sources spectra. The Giessen calculations used the same MV point-source spectra from Mohan and phase space files from linac heads modelled in former publications (see Czarnecki *et al.* 2018 and references therein); for ^{60}Co, a phase space file for an Eldorado-6 unit available from the IAEA data base (Capote *et al.* 2006) was adopted. Both groups used variance reduction techniques implemented in egs_chamber, namely, intermediate phase space storage; photon cross-section enhancement (XCSE) in a 1 cm region surrounding the scoring volume with an XCSE factor of 256 (Giessen) or 512 (Oldenburg), and Russian Roulette with a survival probability of 1/512. The transport and particle production threshold energies were 1 keV for the kinetic energy of electrons (ECUT = AE = 512 keV) and photons (PCUT = AP = 1 keV) to calculate D_{w} and $\overline{D}_{\text{ch-air}}$.

2.3. Experimental determinations

Measurements of k_{Q} were performed at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, for three samples of the PTW Pinpoint 3D type 31022 chamber.

All the chambers were calibrated in the ^{60}Co reference beam available at PTB Braunschweig traceable to the German primary standard of absorbed dose to water (water calorimeter, see Krauss (2006)). The calibrations in high-energy photon beams were performed at two Elekta Precise linear accelerators (Elekta AB, Stockholm, Sweden) available at the metrological accelerator facility at PTB. The nominal accelerating voltages used were 4 MV, 6 MV, 8 MV, 10 MV, 15 MV, and 25 MV, respectively. All measurements were performed in a horizontal beam geometry in a water phantom with dimensions 30 cm × 30 cm × 30 cm which was positioned at a distance SSD = 100 cm from the radiation source. The entrance window of the phantom was made of PMMA with a thickness of 3 mm. A field size of 10 cm × 10 cm at the surface of the phantom was chosen for the measurements. All detectors were positioned with its reference point on the beam axis at a depth of 10 cm (the front window of the phantom was scaled to a water equivalent thickness of 3.45 mm). All chamber readings were corrected for the influence of water temperature and air pressure which were measured continuously by using a PT-100 temperature sensor in the phantom and a barometer mounted in the irradiation room close to the phantom.

In a first step an in-house made monitor chamber, which was mounted on the shadow tray of the linac (Kapsch and Krauss 2009), was calibrated for each of the beam qualities used in this investigation. The calibration coefficient of the monitor chamber was determined as the mean of the calibration coefficients obtained using two secondary standard ionization chambers of types PTW 30013 and PTW 31021 which had previously been calibrated directly in the water calorimeter (primary standard for absorbed dose to water). In a second step, the readings of the three chambers under analysis were measured in the high-energy photon beams simultaneously with the readings of the monitor chamber. For the measurements, both polarities of the chamber voltage were applied in order to assess the polarity correction. Each time after replacing a chamber in the phantom or switching the polarizing voltage it was checked that the chamber readings had reached a stable state before data were recorded. A correction for recombination effects was applied by using the (type-specific) fitting function for ionization chambers of type PTW 31022 given in DIN 6800-2 (2020). After the measurements with all detectors have been done, the calibration measurement of the monitor chamber was repeated in order to check the stability of its calibration coefficient during the course of the measurement.

The k_Q factor for each chamber was determined from the equality of the absorbed doses measured using the monitor (mon) and the ionization chamber under test (ic), that is,

$$D_{\mathrm{w}} = \left(N_{D,\mathrm{w}} M_Q k_{\mathrm{TP}} k_{\mathrm{pol}} k_{\mathrm{s}} k_Q\right)^{\mathrm{ic}} = \left(N_{D,\mathrm{w}} M_Q\right)^{\mathrm{mon}}, \tag{2}$$

from which the k_Q value was obtained as

$$k_Q = \frac{N_{D,\mathrm{w}}^{\mathrm{mon}}}{N_{D,\mathrm{w}}^{\mathrm{ic}}} \frac{M_Q^{\mathrm{mon}}}{M_Q^{\mathrm{ic}}} \frac{1}{\left(k_{\mathrm{TP}} k_{\mathrm{pol}} k_{\mathrm{s}}\right)^{\mathrm{ic}}} \tag{3}$$

The final k_Q value was computed as the average of the values for the three chamber samples.

2.4. Statistical analysis of the data

The results from the three Monte Carlo data sets were combined with the experimentally derived k_Q values to form a single data set. This was fitted with a Mathematica v12 notebook (Wolfram Research Inc, 2020) using the "NonlinearModelFit" empirical function given in Andreo *et al.* (2020)

$$k_Q(\mathrm{TPR}_{20,10}) = \frac{1+\exp\left(\dfrac{a-0.57}{b}\right)}{1+\exp\left(\dfrac{a-\mathrm{TPR}_{20,10}}{b}\right)}, \tag{4}$$

where a and b are fitting parameters specific for the chamber type, and 0.57 represents the $\mathrm{TPR}_{20,10}$ average value typically measured for a ^{60}Co therapy unit which forces $k_Q = 1$ for the reference quality.

Following the discussion on uncertainties in Andreo *et al* (2020), for the present analysis the different input data sets were not weighted statistically, the reason being that the stated relative uncertainties were of different type, combined uncertainties for the experimental data and Type A uncertainties only for the MC results. It was emphasized in that paper that MC calculations do not include Type B uncertainty estimates and, so far, the uncertainty of single and multiple electron scattering theories, their implementation in the different MC systems and the effect of the latter on boundary crossing algorithms and on the condensed-history step mechanics, have never been evaluated.

3. Results

3.1. Monte Carlo calculations for the NE 2571 chamber

The results of the present calculations of the beam quality factors for the NE 2571 chamber type are shown in Fig. 2. They are compared with the corresponding values in the k_Q consensus paper (Andreo *et al.* 2020), which are displayed as the fit to the data using Eq. (4) (Eq. (6) in the consensus paper) and the 95% prediction intervals of the fit. The label "MC-spt" corresponds to Monte Carlo simulations using published point-source spectra as input radiation source, while "MC-phsp" stands for inputs based on phase-space data obtained from detailed linac simulation. Note that for some of the calculations the type A standard uncertainty is smaller than the size of the plot symbols.

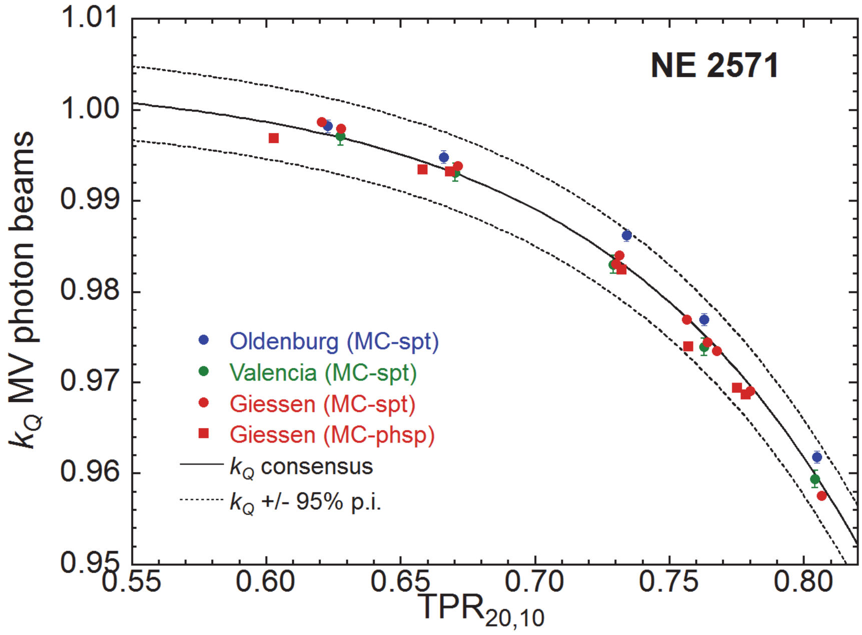

Figure 2. Results of the Monte Carlo calculated k_Q values for megavoltage photon beams obtained by the three groups for a NE 2571 ionization chamber type. The solid line is the fit to the data in the k_Q consensus paper (Andreo et al. 2020) using Eq. (4) and the dashed lines are the 95% prediction intervals of the fit.

3.2. Monte Carlo calculations for the PTW 31022 chamber

The results for the beam quality factors of the PTW PinPoint 3D chamber type 31022 obtained by the three Monte Carlo groups are detailed in Tables 1 to 3, where the $TPR_{20,10}$ values calculated by each group for the spectra used are given, along with the k_Q value obtained and its type A uncertainty (k=1).

Table 1. Beam quality factors k_Q for MV photon beams calculated by the Valencia Monte Carlo group using the penEasy/Penelope code with point-source spectra.

MV spectrum	$TPR_{20,10}$	k_Q	Uncertainty (k=1) [%]
Mohan 4 MV	0.628	0.9972	0.08
Mohan 6 MV	0.670	0.9938	0.08
Mohan 10 MV	0.729	0.9825	0.07
Mohan 15 MV	0.763	0.9753	0.07
Mohan 24 MV	0.804	0.9605	0.07

Table 2. Beam quality factors k_Q for MV photon beams calculated by the Oldenburg Monte Carlo group using the egs_chamber/EGSnrc code with point-source spectra.

MV spectrum	$TPR_{20,10}$	k_Q	Uncertainty (k=1) [%]
Mohan 4 MV	0.623	0.9963	0.04
Mohan 6 MV	0.666	0.9930	0.04
Mohan 10 MV	0.734	0.9832	0.05
Mohan 15 MV	0.763	0.9748	0.06
Mohan 24 MV	0.805	0.9615	0.07

Table 3. Beam quality factors k_Q for MV photon beams calculated by the Giessen Monte Carlo group using the egs_chamber/EGSnrc code. Rows above "Mohan 4 MV" correspond to fully modelled linacs including the linac head; rows below are point-source spectra.

MV phase-space or spectrum	$TPR_{20,10}$	k_Q	Uncertainty (k=1) [%]
Elekta 6 MV	0.668	0.9902	0.09
Siemens KD 15 MV	0.777	0.9703	0.09
Varian X6 MV	0.659	0.9901	0.08
Varian X10 MV	0.735	0.9804	0.10
Varian X15 MV	0.758	0.9742	0.08
Varian X18 MV	0.776	0.9701	0.10
Mohan 4 MV	0.629	0.9958	0.07
Mohan 6 MV	0.672	0.9915	0.07
Mohan 10 MV	0.732	0.9805	0.07
Mohan 15 MV	0.764	0.9726	0.07
Varian 4 MV	0.621	0.9958	0.08
Varian 6 MV	0.662	0.9917	0.07
Varian 10 MV	0.729	0.9803	0.07
Varian 15 MV	0.755	0.9750	0.05
Varian 18 MV	0.780	0.9680	0.05

3.3. Measurements for the PTW 31022 chamber

The PTB measured beam quality factors of the PTW PinPoint 3D chamber type 31022 in various MV photon beam qualities are given in Table 4. They are average values of those obtained for the three samples of the chamber; the uncertainties given are combined standard uncertainties (k=1)

Table 4. Beam quality factors k_Q for MV photon beams measured at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig Elekta Precise linear accelerators.

Nominal linac beam	TPR20.10	k_Q mean	Uncertainty (k=1) [%]
4 MV	0.638	0.9958	0.45
6 MV	0.683	0.9892	0.45
8 MV	0.714	0.9842	0.45
10 MV	0.733	0.9858	0.45
15 MV	0.760	0.9780	0.45
25 MV	0.799	0.9602	0.50

3.4. Fitting the combined results

The fitting parameters for Eq. (4) and the 31 data points of the combined Monte Carlo and experimental data set were

$$a = 1.14435$$
$$b = -0.111303$$

yielding an RMS difference of 0.16%. The fit residuals are displayed in Fig. 3, showing maximum and minimum differences of the data with the fit of 0.45% and -0.30%, respectively.

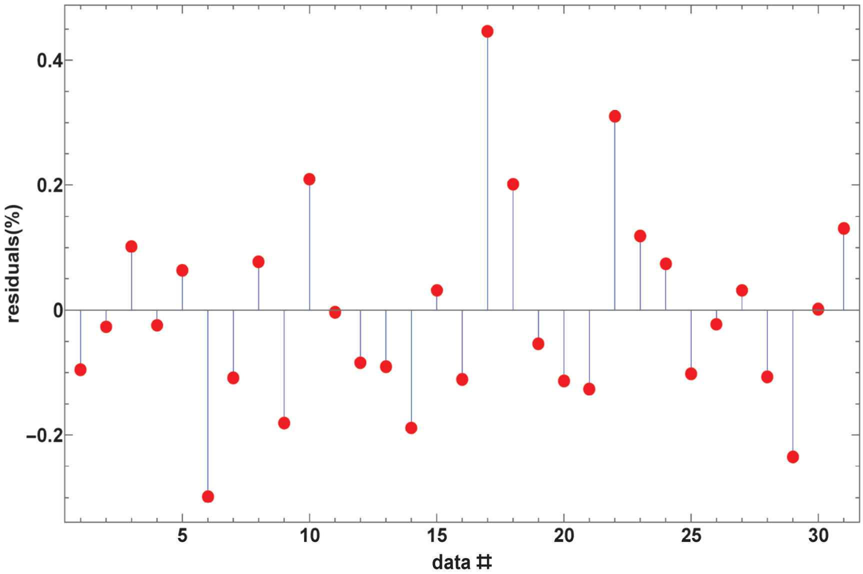

Figure 3. Fit residuals (%) for Eq. (4) and the 31 data points of the combined Monte Carlo-calculated and experimental set.

The results of the regression analysis are shown in Fig. 4, which in addition to the input data and fitted curve, includes the 95% prediction limits of the fit. The uncertainty bars shown in the plot correspond to one standard deviation (k=1) and, as mentioned above, they correspond to Type A uncertainties for the Monte Carlo data and combined uncertainties for the measured values.

The estimated uncertainty of the present fitted k_Q values is, in consistency with the estimates in Andreo *et al* (2020), 0.6%.

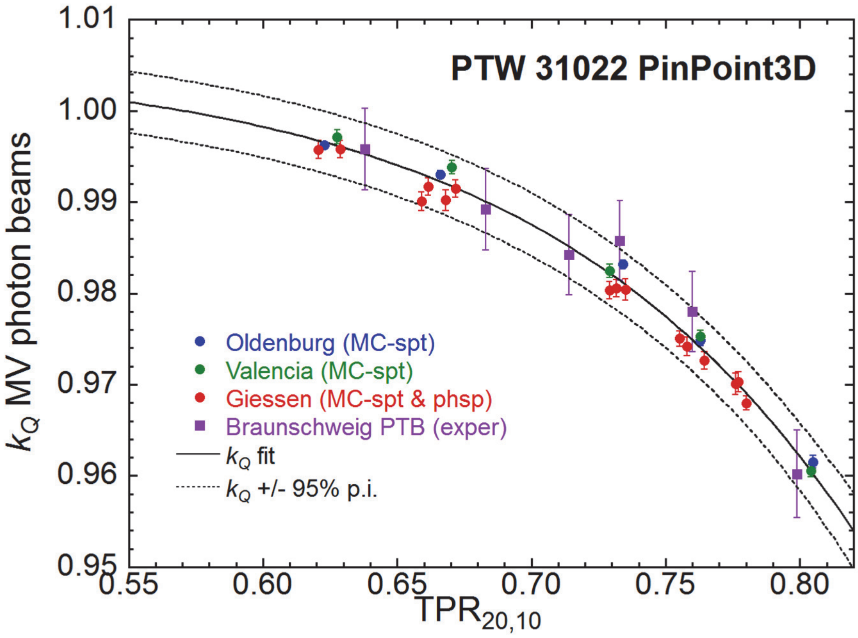

Figure 4. Values of k_Q for megavoltage photon beams obtained from Monte Carlo calculations by three groups (filled circles) and measured at PTB (filled squares) for a PTW 31022 PinPoint 3D ionization chamber type. Uncertainty bars correspond to one standard deviation (k=1) and correspond to Type A uncertainties for the Monte Carlo data and combined uncertainties for the measured values. The solid line is a fit to the data using Eq. (4) and the dashed lines are the 95% prediction intervals of the fit.

4. Discussion

For the simulations of the reference NE 2571 chamber, see Fig. 2, the consistency of the data by the different groups and their agreement with the consensus k_Q values for this chamber was considered highly satisfactory. It should be noted that no significant differences were observed in the results obtained using point-source spectra (e.g. from Mohan *et al.* 1985) and phase-space data obtained from fully modelled linacs including the linac head; in what followed they were presented as a single Giessen data set.

With regard to the data for the PTW PinPoint 3D chamber type 31022 shown in Fig. 4, it is important to emphasize that even though the k_Q values have been calculated by three independent Monte Carlo groups, using two Monte Carlo systems, and measured by one further group, all the data except one single data point fall within the 95% limits of the overall fit; considering however the uncertainty of the measured data, there shouldn't be concern on that specific data point. This shows the overall consistency of the data and that the resulting consensus k_Q can be considered to be robust values estimation for this chamber.

It is also of interest to reflect on the difference between the geometry conditions used in the simulations by the different groups, which although having in common a calculation depth of 10 cm for the megavoltage beams, they differ on the SSD used, 100 cm and 90 cm, and hence on the SCD, 110 cm and 100 cm. For the ^{60}Co beam the Valencia group used the same conditions as for the MV beams, whereas the other groups used the more common SSD of 80 cm and depth of 5 cm. These differences are not patent in Fig. 4, leading to conclude that they do not influence the scatter of the results in a systematic manner.

5. Conclusion

The beam quality factor k_Q has been independently calculated by three Monte Carlo groups and measured by one experimental group; this yielded 25 calculated and 6 measured data points respectively. A fit to the combined data using the empirical function given in the consensus paper by Andreo *et al.* (2020) provides consensus k_Q values for the PTW PinPoint 3D chamber type 31022 in megavoltage photon beams that expand the data set for the update of the IAEA TRS-398 Code of Practice.

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