Measured and Monte Carlo calculated k_Q factors: Accuracy and comparison

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Purpose: The journal *Medical Physics* recently published two papers that determine beam quality conversion factors, k_Q, for large sets of ion chambers. In the first paper [McEwen Med. Phys. **37**, 2179–2193 (2010)], k_Q was determined experimentally, while the second paper [Muir and Rogers Med. Phys. **37**, 5939–5950 (2010)] provides k_Q factors calculated using Monte Carlo simulations. This work investigates a variety of additional consistency checks to verify the accuracy of the k_Q factors determined in each publication and a comparison of the two data sets. Uncertainty introduced in calculated k_Q factors by possible variation of W/e with beam energy is investigated further.
Methods: The validity of the experimental set of k_Q factors relies on the accuracy of the NE2571 reference chamber measurements to which k_Q factors for all other ion chambers are correlated. The stability of NE2571 absorbed dose to water calibration coefficients is determined and comparison to other experimental k_Q factors is analyzed. Reliability of Monte Carlo calculated k_Q factors is assessed through comparison to other publications that provide Monte Carlo calculations of k_Q as well as an analysis of the sleeve effect, the effect of cavity length and self-consistencies between graphite-walled Farmer-chambers. Comparison between the two data sets is given in terms of the percent difference between the k_Q factors presented in both publications.
Results: Monitoring of the absorbed dose calibration coefficients for the NE2571 chambers over a period of more than 15 yrs exhibit consistency at a level better than 0.1%. Agreement of the NE2571 k_Q factors with a quadratic fit to all other experimental data from standards labs for the same chamber is observed within 0.3%. Monte Carlo calculated k_Q factors are in good agreement with most other Monte Carlo calculated k_Q factors. Expected results are observed for the sleeve effect and the effect of cavity length on k_Q. The mean percent differences between experimental and Monte Carlo calculated k_Q factors are −0.08, −0.07, and −0.23% for the Elekta 6, 10, and 25 MV nominal beam energies, respectively. An upper limit on the variation of W/e in photon beams from cobalt-60 to 25 MV is determined as 0.4% with 95% confidence. The combined uncertainty on Monte Carlo calculated k_Q factors is reassessed and amounts to between 0.40 and 0.49% depending on the wall material of the chamber.
Conclusions: Excellent agreement (mean percent difference of only 0.13% for the entire data set) between experimental and calculated k_Q factors is observed. For some chambers, k_Q is measured for only one chamber of each type—the level of agreement observed in this study would suggest that for those chambers the measured k_Q values are generally representative of the chamber type. [DOI: 10.1118/1.3600697]

Key words: k_Q factors, W/e, Monte Carlo, EGSnrc, measurements, dosimetry protocols

I. INTRODUCTION

Two papers[1,2] recently published in *Medical Physics* determined beam quality conversion factors, k_Q, in megavoltage photon beams for large sets of cylindrical ionization chambers. McEwen[1] measured k_Q factors for 27 different ionization chamber types. Muir and Rogers[2] used Monte Carlo simulations to calculate k_Q values for 32 different types of ionization chamber. There are 25 chamber types which overlap between the two studies, allowing a comparison of k_Q factors determined through experiment and Monte Carlo simulation. This work determines the reliability of the k_Q factors obtained in both ways and provides a detailed comparison of measured and calculated k_Q factors. Measured k_Q factors have been determined in previous publications using water calorimetry[3–8] or Fricke dosimetry.[9–12] However, aside from the work of McEwen,[1] experimental determination of k_Q has been limited to only a few chamber types. Additionally, many of the measured values suffer from large uncertainty (in most cases >0.5%) or use Fricke chemical dosimetry, which must be corrected for intrinsic energy dependence. Therefore, the focus of this investigation is only on the measured values of McEwen.[1] However, an internal report,[13] available online, shows the Monte Carlo results with many of the available experimental values of k_Q for all of the ion chambers simulated by Muir and Rogers.[2]

I.A. Summary of previous publications

McEwen[1] measured k_Q factors at the National Research Council of Canada (NRC) using the cobalt-60 irradiator and the Elekta *Precise* linac operated at 6, 10, and 25 MV. Values of k_Q were obtained using the definition of k_Q:

$$k_Q = \frac{N_{D,w}^{Q}}{N_{D,w}^{60Co}}, \tag{1}$$

where $N_{D,w}^{Q}$ is the absorbed dose calibration coefficient in a beam of quality Q, determined as D_w^Q/M where D_w^Q is the absorbed dose to water in a beam of quality Q and the ion chamber measurement, M, is corrected for ion recombination, polarity, temperature and pressure variations, and electrometer response. The majority of primary standards laboratories determine D_w using a calorimeter. The complexity of operation and the time required to carry out calorimetry means that direct measurements are generally limited to a set of laboratory-maintained reference chambers. Values of k_Q factors for other chambers are then determined indirectly by comparison with these reference chambers. The additional uncertainty incurred in this extra step does not contribute significantly to the overall uncertainty in the determination of $N_{D,w}$ and k_Q. At the NRC a set of five reference NE2571 ion chambers were calibrated directly against the primary standard water calorimeter and then used to calibrate other chamber types via

$$N_{D,w,\mathrm{user}} = N_{D,w,\mathrm{ref}} \frac{M_{\mathrm{ref}}}{M_{\mathrm{user}}}. \tag{2}$$

Thus, all measurements of k_Q for other chambers are correlated with the NE2571 measurements. Confidence in all other measurements rests on the accuracy of the calibration of the NE2571 reference chambers; Sec. II B 1 presents an analysis of this issue.

Measured k_Q factors were presented for three photon beam qualities, specified in terms of the photon component of the percent depth-dose at 10 cm, $\%dd(10)_x = 67.2$, 72.6, and 84.4% ($\mathrm{TPR}_{10}^{20} = 0.681$, 0.731, and 0.800).

Characteristics of a suitable reference chamber were defined in the previous work[1] in terms of initial chamber settling, leakage currents, polarity and recombination behavior, chamber stability between calibrations and sensitivity to environmental conditions; using these a list of suitable chambers for clinical reference dosimetry was compiled.

The calculated k_Q factors were determined by simulating the absorbed dose to water, D_w, and the absorbed dose to the air in an ion chamber, D_{ch}, in a cobalt-60 beam and in a beam of quality Q. With the assumption that the average energy deposited per coulomb of charge of one sign released by an electron coming to rest in dry air, W/e, is constant with beam quality, k_Q was calculated using

$$k_Q = \frac{\left(\frac{D_w}{D_{ch}}\right)^{Q}}{\left(\frac{D_w}{D_{ch}}\right)^{^{60}Co}}. \tag{3}$$

Simulations were performed using the egs_chamber usercode of Wulff *et al.*[14] for the EGSnrc Monte Carlo code system.[15,16] Ion chambers were modeled using user manual or blueprint specifications. Photon beams were modeled as collimated point sources using[11] different tabulated spectra. Other publications[17,18] calculate k_Q factors using the same equation [Eq. (3)] and a very similar approach but for a small subset of chambers and, in the case of the work of González-Castaño *et al.*,[18] with much larger statistical uncertainty.

Calculated k_Q factors were presented in terms of a high-precision fit, with the % RMS deviation generally <0.1%, as a function of $\%dd(10)_x$ for each chamber. The fit is of the form

$$k_Q = a + b \times \%dd(10)_x + c \times (\%dd(10)_x)^2 \tag{4}$$

and it is valid for $\%dd(10)_x \geq 62.7\%$.

Both investigations[1,2] of beam quality conversion factors analyzed the overall uncertainties in the k_Q factors that were presented. The relative standard uncertainty on measured k_Q factors amounts to 0.30% for suitable reference chambers. It is larger for chambers that exhibit issues with chamber settling, leakage currents and polarity and recombination behavior.[1] The relative systematic uncertainty on calculated k_Q values (considering correlated uncertainties in photon cross-sections and ignoring possible variation of W/e with energy) amounts to between 0.28% for graphite-walled chambers and 0.39% for A150-walled chambers.[2]

I.B. Possible variation of W/e with beam quality

As discussed previously, the question about whether there is variation of W/e with beam energy is still a significant issue.[2] If W/e does vary with beam energy, it introduces a significant component of uncertainty in both the Monte Carlo calculated values of k_Q as well as those published in dosimetry protocols.[19,20] Experimental determination of k_Q does not depend on the assumption that W/e is constant with photon energy, unlike determination via Monte Carlo simulation. Comparing experimental and Monte Carlo values of k_Q can give an indication of the upper limit on the variation of W/e between cobalt-60 and up to 25 MV beam energies. The investigation below regarding this variation is performed to: (1) stimulate further research on the variation of W/e with beam energy and (2) estimate a realistic uncertainty in calculated k_Q factors due to this possible variation since this has not yet been investigated.

II. METHODS

II.A. Data additional to previously published results

In reviewing the experimental data presented by McEwen[1] it was found that the values presented for the NE2611

TABLE I. Measured results for the NE2611 chambers updated through renormalization and combination of previous data. The uncertainty on these values is 0.33%.

$\%dd(10)_x$	67.2	72.6	84.4
k_Q	0.9938	0.9829	0.9639

chamber type were in error by approximately 0.5% due to a normalization mistake. Subsequently new experimental data were obtained for two NE2611 chambers and these data were combined with the corrected data from previous measurements to provide our best estimate of the NE2611 k_Q factors as presented in Table I.

Since the publication of the paper by Muir and Rogers,[2] one new chamber, the PTW31013, has been simulated for comparison to the experimental results. This chamber is modeled following the model of the PTW31010 chamber of Wulff *et al.*,[17] modified using specifications for the PTW31013 chamber from the PTW Detector Catalog and information obtained from PTW (private communication, 2010). The PTW31010 and the PTW31013 differ primarily in the length of the cavity and electrode. The chamber model for the NE2561 has been updated using detailed drawings of the chamber. The core specifications used for the Monte Carlo simulations of the two chambers are provided in Table II, while fit parameters for the chambers are in Table III. The previous[2] and current models of the NE2561 are very different – the stem has been completely remodeled and the aluminum electrode diameter was increased and modeled as hollow. Although the changes are significant, the differences between the updated calculated k_Q factors of this work and those presented in the previous publication[2] are generally less than 0.3%. This new model of the NE2561, for which fit coefficients are provided in Table III, is our best estimate of the model of a realistic NE2561 ion chamber.

The NE2561 and NE2611 chambers are almost identical; the only difference is that the protective sleeve that holds the thimble on is composed of Polyoxymethylene (POM, trade name Delrin) for the NE2561 and Aluminum for the NE2611. The change was made because of radiation damage causing cracks in the POM of the NE2561. Boas *et al.*[21] reported that the relative responses of the NE2561 and NE2611 chambers differ by about 2%. However, follow-up measurements did not yield any difference in response at the 0.5% level.[22] Monte Carlo simulations of both chamber models yields a maximum difference of only 0.3% in k_Q factors. Measurements performed at NRC for the two chambers do not show differences at the 0.1% level. In addition, data from the National Physical Laboratory,[23] covering a large number of chambers characterized over several years, show no significant difference between the two chamber types. The conclusion of this study was that the chambers can be considered as a single type.

TABLE III. Fit coefficients to Monte Carlo calculated k_Q factors for new/updated models of the PTW31013 and NE2561/2611 chambers. The difference between NE2561 and NE2611 chambers is that the protective sleeve, which attaches the thimble, is composed of Polyoxymethylene (POM, trade name Delrin) or Aluminum for the two chambers, respectively.

	a	b ($\times 10^3$)	c ($\times 10^5$)	% RMS deviation
PTW31013	0.97252	1.957	−2.498	0.05
NE2561	0.97216	1.977	−2.463	0.05
NE2611	0.93787	2.969	−3.190	0.05

The previous publications[1,2] employed filtered beams to determine k_Q factors. The tabulated spectrum used by Muir and Rogers[2] which most closely matches the output of the Elekta *Precise* linac used by McEwen[1] is that for the Elekta SL25 25 MV beam[24] with $\%dd(10)_x = 82.8$ compared to 84.4% for the NRC Elekta *Precise* linac. As mentioned in the previous publication,[2] calculations of k_Q varied by less than 0.1% when using BEAMnrc models compared to tabulated spectra for a subset of beams. Additional calculations are performed to determine k_Q for the NE2571 chamber using the BEAMnrc model of the 25 MV Elekta *Precise* linac beam of Tonkopi *et al.*[25] to compare to calculations performed using photon spectra. The supplementary calculations agree with the fit to Monte Carlo calculated k_Q factors (using photon spectra) within the statistical uncertainty of 0.1% of the k_Q factors.

II.B. Validity of results

II.B.1. Establishing confidence in NE2571 measurements

The experimental method used by McEwen[1] – deriving k_Q factors by comparison with a set of reference chambers—leads to strongly correlated data. First, all k_Q factors are dependent on the original comparison of the NE2571 reference chambers with the primary standard water calorimeter. Second, all subsequent measurements are a ratio of each ion chamber to the reference chambers. Both issues have been reviewed in detail and the results are presented here.

TABLE II. Specifications for the PTW31013 and NE2561/2611 chambers. The materials are Polymethylmethacrylate (PMMA), Graphite (Gr), and Aluminum (Al).

	Wall		Electrode			Active cavity	
Chamber (volume/cm^3)	Material	Thickness (mm)	Material	Radius (mm)	Length (mm)	Radius (mm)	Length (mm)
PTW31013 (0.3)	PMMA/Gr	0.55/0.15	Al	0.45	14.25	2.75	16.25
NE2611/2561 (0.3)	Gr	0.53	Al	1.0[a]	6.5	3.7	9.0

[a]The NE2561 has a hollow electrode with a 0.2 mm thick Aluminum shell. The air inside the Aluminum layer is not considered part of the active cavity volume.

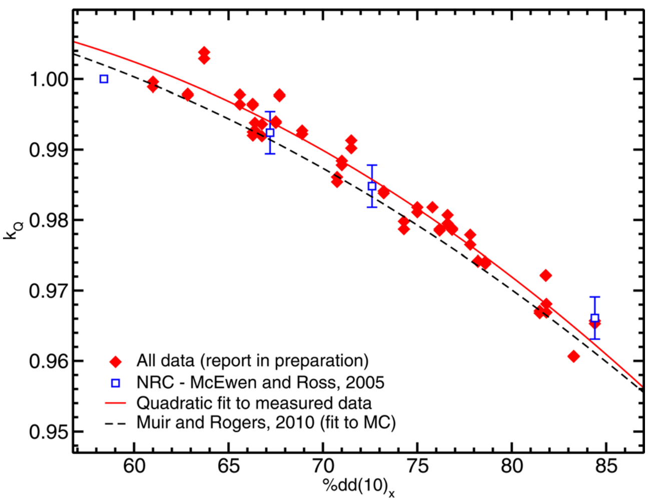

FIG. 1. Comparison of the measured k_Q factors of Ref. 36 and those from a large comparison of primary standard laboratories [Stucki, G, private communication (comparison report in preparation)] for the NE2571 ion chamber from several primary standards laboratories with the fit to Monte Carlo calculated values (Ref. 2). Error bars represent systematic uncertainties on the measured values.

The main concern for the second issue is the stability of the reference chambers both during the relatively short timescale of the new set of k_Q measurements reported by McEwen[1] and the longer time elapsed between those measurements and the calorimetry measurements to determine k_Q for the NE2571. The stability of the NRC NE2571 chambers has been independently monitored through measurements in a cobalt-60 reference field. Over the period 1995–2010, the standard deviation on the calibration coefficients obtained in the cobalt-60 field is typically 0.06% for all the NE2571 reference chambers used. This uninterrupted data collection covers the entire period of water calorimetry and k_Q measurements required for the results reported by McEwen[1] and therefore one can conclude that reference chamber stability is not a significant component of uncertainty in the experimental determination of k_Q for other chamber types.

The absolute accuracy of NE2571 k_Q factors requires some form of external comparison. McEwen[1] (in Fig. 1 of that paper) showed that k_Q factors obtained using the NRC primary standard water calorimeter were independent both of the accelerator beam used and when the measurements were made. This is impressive, but not sufficient. Figure 1 shows the results of a large comparison [Stucki, G, private communication (comparison report in preparation)] of primary standard laboratories, where $N_{D,w}$ factors were determined at each laboratory for the same ion chambers to compare standards. Only the NRC data are specifically identified and it can be seen that: (i) there is very good agreement among all the laboratories involved and (ii) the NRC data are within 0.3% of the mean of all results shown by the solid line. We can confidently state that the NE2571 k_Q factors obtained at the NRC and used as the basis for the results presented by McEwen[1] are accurate at the level of uncertainty of 0.3% reported in that paper.

II.B.2. Representative nature of experimental k_Q factors

It is rarely possible to characterize a large number of chambers of any one type, except in the situation of well-established national calibration services [e.g., the data presented on the NE2561/NE2611 chambers by the National Physical Laboratory (NPL)[23]]. This study concluded that chamber-to-chamber variation in k_Q values for these chambers is not significant, being less than 0.13%. However, most measurements of k_Q factors have typically involved only one to three chambers of each type—the specific number of chambers of each type characterized by McEwen[1] was provided in Table 7 of that work. Drawing general conclusions using such a small sample can be potentially hazardous. In particular, agreement between measured and calculated k_Q factors for a single chamber cannot be taken as demonstrating that the measured data are typical of the chamber type as a whole. Monte Carlo calculated k_Q factors represent the ideal chamber using specifications provided by the chamber manufacturers. Therefore, if a given chamber behaves exactly as the manufacturer intends, the Monte Carlo calculated k_Q factors should give accurate results for reference dosimetry. Measured values of k_Q are relevant for the specific chamber for which the measurements were performed. Although generally not significant for cylindrical ion chambers as demonstrated by the NPL data above[23] and the data for multiple chambers in Seuntjens *et al.*,[4] if there are chamber-to-chamber variations for chambers of the same type, agreement between measured and calculated k_Q factors may be fortuitous. However, by analyzing the results for the large number of different chambers as a single data set, one can make stronger statements than would otherwise be possible.

II.B.3. Monte Carlo calculations of k_Q: Comparison with other publications and self-consistency

In Fig. 2 of our preceding work,[2] Monte Carlo calculated k_Q factors for the NE2571 and Exradin A12 chambers were plotted for comparison to other Monte Carlo calculated k_Q factors[17,26] and measured k_Q factors.[3,4,7] The calculated NE2571 results are in excellent agreement with other publications – within 0.7% of all measured and Monte Carlo calculated results. The fit to Monte Carlo calculated NE2571 k_Q factors[2] agrees within 0.78% of all of the individual measured values provided in Fig. 1. In addition, agreement within 0.24% is observed between the fit to calculated NE2571 k_Q factors[2] and the quadratic fit to all measured results shown by the solid line of Fig. 1. The Monte Carlo calculated k_Q values for the Exradin A12 are up to 0.6% lower than the measured k_Q factors of Seuntjens *et al.*[4] and show agreement with the less precise Monte Carlo calculated factors of Tantot and Seuntjens[26] well within the statistical uncertainties of that work (up to 0.5%). As mentioned above, Monte Carlo calculations of k_Q agree within the statistical uncertainty (up to 1%, although within 0.7% for most chambers) of calculated k_Q factors provided by González-Castaño *et al.*[18] for all chambers except for the IBA CC01. We performed calculations of the IBA CC01 with the same specifications of the

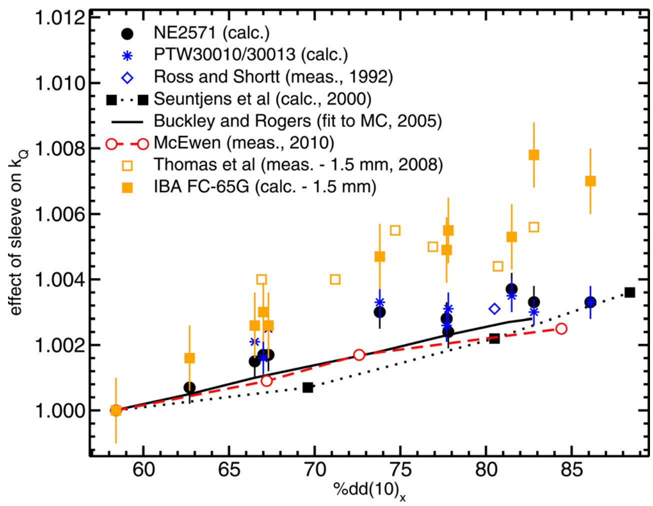

FIG. 2. The effect of a 1 mm PMMA sleeve on k_Q; comparison of Monte Carlo results for the NE2571 and PTW30010/30013 from Ref. 2 with literature values. Error bars represent statistical uncertainties in the Monte Carlo calculations. Measured data are from Refs. 1, 27, 29, while the fit to Monte Carlo calculations for a 1 mm sleeve is from Ref. 28 Uncertainties on experimental data are not shown. Lines are used that connect symbols to show the trend of some data. The lightly colored square symbols are calculations (closed) and measurements (open) for a 1.5 mm thick sleeve on the IBA FC-65G chamber.

central electrode as used by González-Castaño *et al.*[18] (private communication) but no improvement in agreement between the two sets of calculations was observed. The major difficulty with simulating small ionization chambers is that obtaining tight statistical uncertainty requires a significant amount of computing time. Statistical fluctuations in the work of González-Castaño *et al.*[18] for the small ionization chambers are likely the cause of the discrepancy between the two sets of Monte Carlo calculations. We therefore do not consider this disagreement significant in terms of the accuracy of the Monte Carlo calculations.

The effect of a 1 mm thick PMMA sleeve on ion chamber response, either measured or calculated through Monte Carlo simulations, has been studied in great detail in the literature.[1,4,27,28] This provides an excellent method of examining the reliability of Monte Carlo calculated k_Q factors. Our previous study[2] allows an investigation of the sleeve effect in two ways. The PTW30010 and PTW30013 ion chambers were modeled as identical chambers as indicated by the specifications in the PTW user manual. However, the 30 010 is not inherently waterproof, requiring a sleeve in the model, while the 30 013 does not require a sleeve. In addition, calculations of k_Q for the NE2571 were performed[2] with and without a waterproofing sleeve (see Fig. 2 of that work). Comparing the k_Q values for two identical chambers with and without a waterproofing sleeve allows an analysis of the sleeve effect normalized at cobalt-60. Literature values are normalized to unity in a cobalt-60 beam in the same way for comparison. Figure 2 shows agreement (within 0.12% of a linear fit to the Monte Carlo calculated results) between the ratio of k_Q values with and without a sleeve[2] compared to experimental and calculated values of the ratio of ion chamber response with and without a sleeve in a beam of quality Q to that in a cobalt-60 beam.

Supplementary Monte Carlo simulations are performed for the IBA FC65-G with and without a 1.5 mm PMMA sleeve for comparison to the results of Thomas *et al.*[29] The two sets of results are in agreement within 0.17%, despite the noise in the measured and calculated data. The Monte Carlo calculations shown in Fig. 2 confirm that there is, in fact, variation of the sleeve effect with beam quality. Additionally, the effect of a 1.5 mm PMMA sleeve on k_Q factors is as large as 0.7% at high energies, which would result in a significant error in the calibration of these radiotherapy sources if the sleeve effect were ignored. This confirms the appropriateness of the recommendation of TG-51[19] that a water-proofing PMMA sleeve should be no more than 1 mm thick.

The differences between the Exradin A12 and A12S and the IBA CC25 and CC13 models are mostly in the length of the cavity. Wang and Rogers[30] noted that replacement correction factors, P_{repl}, vary by $0.2 \pm 0.1\%$ with cavity length, hence one expects that k_Q is nearly independent of cavity length. Differences between calculated k_Q factors for chambers, where the cavity length is the main difference between models are less than 0.12% (Ref. 2).

For clinical reference dosimetry, the standard for many years has been the graphite-walled, aluminum electrode Farmer-type chamber and the study of Muir and Rogers[2] included three such chambers—the NE2571, IBA FC-65G, and PTW30012. A comparison of such similar chambers is useful in reviewing the accuracy of the Monte Carlo results (i.e., for checking the accuracy of model construction). Despite the similarities there are two potentially significant differences:

1. The NE2571 and PTW30012 chambers require a waterproofing sleeve but the IBA FC65-G chamber is inherently waterproof.
2. All of the chambers have aluminum electrodes but different wall thicknesses – 0.36 mm (NE2571), 0.425 mm (PTW30012), and 0.43 mm (FC-65G).

Both factors impact the calculated k_Q factors.
A number of calculations were carried out:

(a) NE2571, 0.36 mm wall, no waterproofing sleeve,
(b) NE2571, 0.36 mm wall, sleeve included,
(c) NE2571, 0.425 mm wall (for comparison, thickness increased on the outside), sleeve included,
(d) PTW30012, 0.425 mm wall, sleeve included,
(e) IBA FC-65G, 0.43 mm wall, no waterproofing sleeve and,
(f) IBA FC-65G, 0.43 mm wall, with 1 mm sleeve (supplementary calculations performed for this comparison).

If one ignores details of the chamber stem then (c) and (d) should yield identical k_Q factors. Calculations of k_Q factors for (c) and (f) should also yield identical k_Q factors. The stems of chambers (c) and (f) are very different, with the

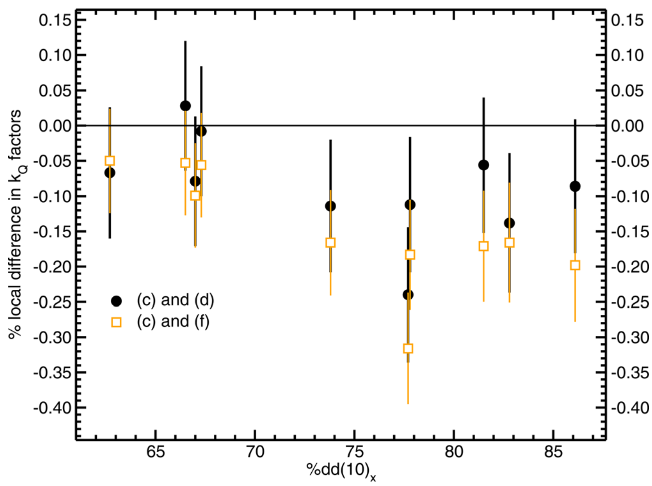

FIG. 3. Percent difference between the Monte Carlo calculated k_Q values for chambers (c) the NE2571 with a 0.425 mm wall and waterproofing sleeve calculated for comparison to (d) the PTW30012 with a 0.425 mm wall with a waterproofing sleeve, as well as (c) and (f) the IBA FC-65G chamber with a 0.43 mm wall and waterproofing sleeve. Error bars represent statistical uncertainties on the calculations.

NE2571 stem based on that of La Russa *et al.*[31] and the IBA FC-65G stem composed of solid C552 with an aluminum electrode running through it. The PTW30012 stem is similar to that of the NE2571 but with minor differences in specifications.

Figure 3 shows the results of this investigation. As can be seen, the differences are small, indicating no significant errors in the model constructions and/or dose calculations. There appears to be a small residual effect (up to 0.3%) but this is consistent with an effect due to small differences in the stem construction and statistical fluctuations. The stem effect is calculated for chambers (c) and (f) and it is confirmed that they differ by 0.3% at the $\%dd(10)_x$ of 77.7% (using the spectrum for the Siemens KD 18 MV beam[23]). This beam appears to give outlying results for the stem effect and hence the relative k_Q factors although we are not sure of the reason for this.

In summary, these various additional consistency checks imply that the Monte Carlo calculations and associated chamber models are performing satisfactorily.

III. RESULTS

III.A. Comparison between the two data sets

Table IV gives the percent differences between experimental and calculated k_Q values, the standard uncertainty on the measured and calculated k_Q values for each chamber, as well as the χ^2 per degree of freedom (df) for each chamber and for each energy. The percent difference is calculated for chamber i as

$$\Delta_i = \frac{k_{Q,i}(\text{calculated}) - \mathrm{k_{Q,i}}(\text{measured})}{k_{Q,i}(\text{measured})} \times 100\%, \tag{5}$$

so that a negative percent difference indicates a higher measured than calculated k_Q factor. The χ^2/df is determined via

$$\chi^2/df = \frac{1}{f}\sum_{i=1}^{f} \frac{\Delta_i^2}{s_m^2 + s_c^2}, \tag{6}$$

where f is the number of degrees of freedom (3 beams for each chamber or 26 chambers for each energy), and s_m and s_c are the standard uncertainties on the measured and calculated k_Q factors, respectively. The χ^2/df or reduced χ^2 is less than 1.0 for all chambers at each energy, indicating agreement between experimental and Monte Carlo calculated k_Q values. Calculating the reduced χ^2 for each chamber by summing over energies results in only one chamber with a reduced χ^2 larger than unity, indicating a significant discrepancy for that chamber. This chamber, the IBA CC01, is not considered suitable for reference dosimetry[1] and this type of deviation is perhaps expected.

Table IV shows that all of the Monte Carlo calculated k_Q factors for the Exradin C552-walled ion chambers are up to 0.7% lower than the experimental values. The C552-walled chambers of IBA do not exhibit such a large discrepancy. To investigate this discrepancy, a sample of the C552 used for the Exradin chambers was obtained from the manufacturer. Chemical analysis, using x-ray fluorescence, showed some differences in composition to that being used for the Monte Carlo calculations. However, simulations performed using the composition of C552 obtained through analysis of the sample gave k_Q values that are unaffected within the statistical uncertainty of the calculations. Perhaps what is most surprising is that all of the Exradin chambers were modeled from blueprints, so one might expect that with more accurate modeling these chambers would show better agreement with experimental results compared to chambers from other manufacturers. Except for the CC01 chamber, information about the composition and specification of the IBA chamber stems were not available, so these chambers have been modeled with a solid C552 stem. Exradin chambers were modeled with a detailed stem using blueprints. However, for some of these chambers (the Exradin A12, A19, A2, and A18) simplified models have been created and the results compared to those obtained using models from chamber blueprints. For the Exradin A12, A2 and A18 chambers, the calculated results using simplified models are up to 0.2% closer to measured results than calculations performed using the blueprint models. For the Exradin A19 chamber, the difference between results calculated using the simplified and blueprint models is up to 0.43% in the highest energy beam. Further study is required to explain the trend between measurements and calculations for the C552-walled chambers. The k_Q factors calculated with simplified models are actually closer to the measured results than those calculated with the blueprint models. This suggests that the k_Q factors calculated for IBA C552-walled chambers (which use very simple models for the stem) exhibit misleading agreement with experimental values. A larger discrepancy is expected between experimental and Monte Carlo calculated k_Q factors for C552-walled IBA chambers with a more realistic stem; this topic will be discussed below in the context of possible variation in W/e.

TABLE IV. Percentage difference $\left(\Delta = \frac{k_Q(calc.) - k_Q(meas.)}{k_Q(meas.)}\right)$ between experimental (Ref. 1) and Monte Carlo calculated (Ref. 2) k_Q factors for each energy and chamber. Chambers which are not suitable for reference dosimetry are in italics. Chamber wall and electrode (el.) materials are given in brackets. Standard uncertainties on experimental and Monte Carlo values are provided in percent for each chamber. The χ^2/df is calculated at all energies for each chamber and for all chambers at each energy.

Chamber (wall, el.)	Nominal MV/ $\%dd(10)_x$ 6/67.2	10/72.6 Δ (%)	25/84.4	Standard Uncertainty (%) Measured	Calculated	χ^2/df (all energies)
NE						
2571[a] (Gr, Al)	−0.16	−0.19	−0.45	0.30	0.28	0.52
2581[b] (A150, A150)	−0.12	−0.05	−0.48	0.30	0.39	0.35
2611[c] (Gr, Al)	−0.05	0.24	−0.28	0.33	0.28	0.25
Capintec						
PR-06C[d] (C552, C552)	−0.16	−0.26	−0.36	0.30	0.36	0.33
PTW						
30010 (PMMA/Gr, Al)	0.15	0.12	0.00	0.30	0.31	0.06
30012 (Gr, Al)	0.12	0.24	0.00	0.30	0.28	0.15
30013 (PMMA/Gr, Al)	0.16	0.37	0.16	0.30	0.31	0.34
31010 (PMMA/Gr, Al)	0.28	0.81	0.23	0.51	0.31	0.74
31013 (PMMA/Gr, Al)	0.00	0.33	0.21	0.30	0.31	0.28
31014 (PMMA/Gr, Al)	0.06	−0.06	−0.45	0.54	0.31	0.19
31016 (PMMA/Gr, Al)	−0.32	−0.05	−0.21	0.59	0.31	0.11
Exradin[e]						
A12 (C552, C552)	−0.22	−0.33	−0.62	0.30	0.36	0.83
A12S (C552, C552)	−0.26	−0.11	−0.49	0.30	0.36	0.50
A19 (C552, C552)	−0.17	−0.27	−0.70	0.30	0.36	0.90
A18 (C552, C552)	−0.38	−0.27	−0.59	0.30	0.36	0.86
A1SL (C552, C552)	−0.28	−0.28	−0.54	0.32	0.36	0.65
A14SL (C552, SPC)	−0.18	−0.22	0.14	0.61	0.36	0.07
A16 (C552, SPC)	0.09	−0.10	0.22	0.80	0.36	0.03
IBA						
FC-65G (Gr, Al)	−0.01	−0.12	−0.15	0.30	0.28	0.07
FC-65P (POM, Al)	0.10	−0.08	−0.04	0.30	0.32	0.03
FC-23C (C552, C552)	−0.07	−0.14	−0.16	0.30	0.36	0.07
CC25 (C552, C552)	−0.27	−0.22	−0.30	0.30	0.36	0.32
CC13 (C552, C552)	−0.13	0.02	−0.02	0.30	0.36	0.03
CC08 (C552, C552)	−0.21	−0.02	−0.18	0.34	0.36	0.11
CC04 (C552, C552)	0.03	−0.06	−0.08	0.37	0.36	0.01
CC01 (C552, Steel)	−0.08	−1.05	−0.87	0.43	0.36	1.97
χ^2/df (all chambers)	0.14	0.39	0.60	—	—	—
χ^2/df (ref. chambers)	0.17	0.35	0.63	—	—	—

[a]Manufactured by QADOS.
[b]No longer manufactured.
[c]Manufactured by NPL.
[d]Manufactured by Capintec.
[e]Manufactured by Standard imaging.

Figure 4 presents histograms of the percent differences between experimental and Monte Carlo calculated k_Q factors for the entire overlap between the two data sets, as well as histograms showing the subset of chambers considered suitable for reference dosimetry, for each nominal linac energy. The mean and standard deviation of the sample are displayed on each plot. Overall, the agreement is very good with some outliers, mostly those chambers that are not suitable for reference dosimetry. However, even with these outliers, the maximum percent difference between experimental and calculated k_Q values is only 1.05%. At 6 MV, the mean percent difference is −0.08 and −0.10% for all and reference chambers, respectively, with a very tight distribution; the standard deviation of the sample is 0.17% for both samples. For the 10 MV beam, the mean percent difference is −0.07 or −0.06 for all and reference chambers, respectively. The standard deviation of the sample is slightly larger than that for the 6 MV beam, being 0.32% for the entire sample and 0.23% for reference chambers. Both distributions have a mean percent difference very close to zero and much less than the standard combined uncertainty of both studies, indicating the excellent agreement between the two data sets. However, at 25 MV the mean percent differences are −0.23 and −0.25% with a standard deviation of the sample of 0.31 and 0.28% for the entire sample and only reference chambers, respectively. Again, this deviation is less than the combined standard uncertainty in

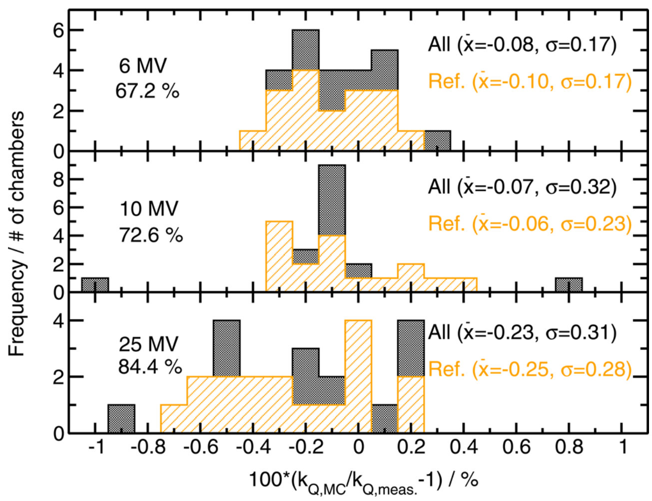

FIG. 4. Histograms comparing measured k_Q values of Ref. 1 and calculated k_Q factors of Ref. 2. There are 17 chambers in the reference set (hashed area) and 26 in the full set of chambers (solid), which includes chambers not considered suitable for reference dosimetry (Ref. 1).

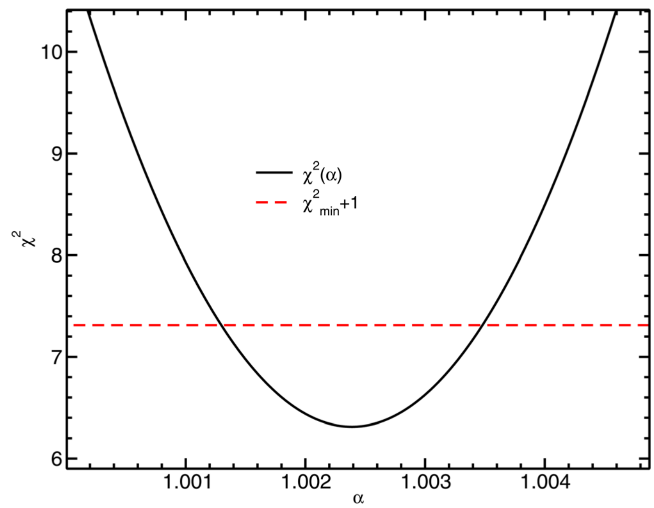

FIG. 5. Estimation of the upper limit on the variation of W/e with beam energy for the subset of 17 reference chambers. The variable α represents the ratio $(W/e)^{Q}_{^{60}Co}$.

both studies but does indicate a systematic difference between the two data sets, with the Monte Carlo calculated values being lower on average than the experimentally determined values at high energy.

III.B. Variation of W/e with beam energy

If there is variation in W/e from cobalt-60 to 25 MV beam energies, then the equation used for the determination of Monte Carlo calculated k_Q factors becomes

$$k_Q = \alpha\left(\frac{D_w}{D_{ch}}\right)^{Q}_{Co}, \quad \text{where } \alpha = \left(\frac{W}{e}\right)^{Q}_{Co}. \tag{7}$$

Replacing Δ_i in Eq. (6) with

$$\Delta_i = \frac{\alpha \times k_{Q,i}(calculated) - k_{Q,i}(\text{measured})}{k_{Q,i}(\text{measured})} \tag{8}$$

and calculating χ^2 for the 25 MV beam as a function of α, one obtains Fig. 5 for the subset of reference chambers. Although the values of χ^2_{min} are different for the subset of reference chambers and all chambers, the same value of α is obtained for both data sets. The uncertainty on this value is determined by taking the corresponding values of α for $\chi^2_{min}+1$ (Ref. 32) giving $\alpha = 1.0024 \pm 0.0011$, which is independent of the data set used. Finally, assuming that the value of α is normally distributed and using the quantiles of the normal distribution from Brandt,[33] an upper limit on the variation of $(W/e)^{25\,\text{MV}}_{^{60}Co}$ is obtained as 1.0029, 1.0038, and 1.0042 with confidence levels of 68, 90, and 95%, respectively. At the 95% confidence level, the value of W/e is not decreasing with energy—that is, the lower limit is consistent with unity, which would indicate constancy of W/e with beam energy. The limit on the variation for the lower energies is less.

This analysis takes no special account of the differences between IBA and Exradin C552-walled ion chambers. To test the effect of using simplified IBA chamber models on the upper limit on the variation of W/e with energy presented above, the method is repeated after reducing Monte Carlo calculated k_Q factors for IBA C552-walled chambers by 0.2%, the amount suggested by the difference in k_Q factors calculated with the blueprint and simplified Exradin chamber models. In the worst case (using only the subset of reference chambers) the results yield an upper limit on $(W/e)^{25\,\text{MV}}_{^{60}Co}$ of 1.0032, 1.0041, and 1.0045 with confidence levels of 68, 90, and 95%, respectively. This indicates that using simplified models for the IBA chamber stems has an insignificant effect on the above analysis.

In the previous paper,[2] the question remained unanswered about what to take as the combined uncertainty on Monte Carlo calculated k_Q factors. Assuming that photon cross-sections are correlated and taking the variation of W/e from cobalt-60 to 25 MV beam at the 68% confidence level calculated in this work as the worst case estimate of the uncertainty in the variation of W/e, one obtains an estimate of the uncertainty on calculated k_Q factors. Adding in quadrature this uncertainty in W/e of 0.29% with the correlated uncertainty on k_Q factors without W/e from Table VI of the previous work,[2] the uncertainty in Monte Carlo calculated k_Q factors is between 0.40% for graphite-walled chambers and 0.49% for A150-walled chambers.

IV. DISCUSSION AND CONCLUSIONS

Overall, outstanding agreement is observed between experimental and Monte Carlo calculated beam quality conversion factors. There is a 0.13% mean percent difference for the entire data set with a sample % RMS deviation of 0.31%. The χ^2/df for the whole data set is only 0.38. The agreement is well within the estimated uncertainties. This level of agreement suggests that on the whole the chambers investigated experimentally are representative of the individual types.

Although well within uncertainties, systematic differences are noted between experimental and Monte Carlo calculated k_Q factors for the Exradin C552-walled chambers.

Despite some measures that have been taken to determine the source of the difference, further research is required to explain the discrepancies.

McEwen[1] used a linear accelerator which employs a flattening filter and the spectra used by Muir and Rogers[2] were calculated using models of linear accelerators with flattening filters.[23,34,35] Therefore, the above analysis might only apply to filtered beams. In particular, the significant effects in beams without flattening filters calculated for ion chambers with electrodes with $Z > 13$[37] have not been investigated here.

An upper limit on the variation of W/e from cobalt-60 to 25 MV beam energies is determined to be 0.42% with 95% confidence (0.29% with 68% confidence). If the IBA ion chamber calculations are adjusted to include the effect of using a model with a detailed stem, this upper limit changes by only 0.03% indicating an insignificant effect from the amount of detail in the chamber stem in this situation.

Using the results from the previous work[2] with the upper limit on the variation of W/e calculated here, a final assessment of the uncertainty on Monte Carlo calculated k_Q factors is between 0.40 and 0.49% depending on the wall material used for chamber construction.

Monte Carlo calculated k_Q factors reflect general chamber dimensions as given by the manufacturer while experimental k_Q factors are relevant for the specific ion chamber for which measurements were made. Measured k_Q factors obtained for the user's specific ion chamber would still be more accurate. However, the exceptional agreement observed here gives great confidence in adopting Monte Carlo calculated k_Q factors for updated dosimetry protocols.

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