Beam quality conversion factors for parallel-plate ionization chambers in MV photon beams

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Purpose: To investigate the behavior of plane-parallel ion chambers in high-energy photon beams through measurements and Monte Carlo simulations.
Methods: Ten plane-parallel ion chamber types were obtained from the major ion chamber manufacturers. Absorbed dose-to-water calibration coefficients are measured for these chambers and k_Q factors are determined. In the process, the behaviors of the chambers are characterized through measurements of leakage currents, chamber settling in cobalt-60, polarity and ion recombination behavior, and long-term stability. Monte Carlo calculations of the absorbed dose to the air in the ion chamber and absorbed dose to water are obtained to calculate k_Q factors. Systematic uncertainties in Monte Carlo calculated k_Q factors are investigated by varying material properties and chamber dimensions.
Results: Chamber behavior was variable in MV photon beams, especially with regard to chamber leakage and ion recombination. The plane-parallel chambers did not perform as well as cylindrical chambers. Significant differences up to 1.5% were observed in calibration coefficients after a period of eight months although k_Q factors were consistent on average within 0.17%. Chamber-to-chamber variations in k_Q factors for chambers of the same type were at the 0.2% level. Systematic uncertainties in Monte Carlo calculated k_Q factors ranged between 0.34% and 0.50% depending on the chamber type. Average percent differences between measured and calculated k_Q factors were -0.02%, 0.18%, and -0.16% for 6, 10, and 25 MV beams, respectively.
Conclusions: Excellent agreement is observed on average at the 0.2% level between measured and Monte Carlo calculated k_Q factors. Measurements indicate that the behavior of these chambers is not adequate for their use for reference dosimetry of high-energy photon beams without a more extensive QA program than currently used for cylindrical reference-class ion chambers.
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I. INTRODUCTION

Plane-parallel ionization chambers are commonly used for reference dosimetry of electron beams. However, very few investigations have used this type of ion chamber in photon beams,[1–6] mostly focusing on behavior in cobalt-60, so there is little information on their behavior in clinical photon beams. Additionally, parallel-plate chambers were not included in protocols for photon beam reference dosimetry[7,8] for two reasons:

1. At the time that the protocols were written, insufficient data were available—specifically P_{wall} correction factors for high-energy photon beams—to perform analytic k_Q calculations for parallel-plate chambers. Therefore, it was not possible to provide k_Q factors using the methods on which the protocols relied.
2. There was measured evidence for up to 3.6% variation of photon beam correction factors for plane-parallel chambers of the same type.[3] This is unacceptably high for reference dosimetry—if a calculated beam quality conversion factor for a representative chamber were provided, significant errors would be introduced due to this chamber-to-chamber variation.

Recently, the use of plane-parallel chambers in MV photon beams has received renewed interest.[2] It is also now possible to perform *ab initio* calculations of k_Q using Monte Carlo simulations,[9–11] so missing data for plane-parallel chambers need no longer be a problem. It is even possible to perform analytic calculations with the method used by absorbed dose protocols for reference dosimetry[7,8] with the emergence of new studies that provide P_{wall} corrections.[4–6,12,13] McEwen[14] showed that it is feasible to provide measured k_Q factors for a large set of ion chambers. Kapsch *et al.*[15] used cross-calibration in electron beams and ^{60}Co calibrations to show that measured chamber-to-chamber variation of perturbation

factors for the Roos, Markus, and Advanced Markus chamber types in cobalt-60 are now less than 1.1% within a single chamber type. Kapsch and Gomola[2] recently showed that chamber-to-chamber variation of k_Q factors in photon beams is no longer as significant (less than 0.7% spread in values for ten chambers of each type), at least for two chamber types from one manufacturer.

These results appear to open up the possibility of using parallel-plate ionization chambers for high-energy photon beam reference dosimetry. Therefore, the purpose of this study is to:

(i) provide the first large-scale study of all available plane-parallel chambers from the major ion chamber manufacturers to characterize their behavior in photon beams,
(ii) provide, based on characterization measurements, some recommendations regarding operating conditions (e.g., appropriate bias voltages) and a recommendation on the ultimate use of these chambers for reference photon beam dosimetry,
(iii) supply measured beam quality conversion factors for the chambers in these beams, and
(iv) disseminate Monte Carlo calculated k_Q factors for plane-parallel chambers in photon beams.

II. METHODS

The procedures adopted here are very similar to those of our recent publications[9,14,16] for cylindrical chambers. Therefore, only a brief review is presented here, highlighting specific differences in methods.

II.A. Measurements: Chamber performance and k_Q factors

Several plane-parallel ionization chambers were obtained from ion chamber manufacturers. These include (numbers in parentheses indicate the number of chambers of each type obtained):

PTW—Roos (2), Markus (2), Advanced Markus (2),

Exradin—A11 (2, one of which was obtained before the manufacturer made major changes in chamber construction), A10 (1), P11TW (1), P11 (1),

IBA—NACP-02 (4, two obtained when Scanditronix was manufacturing these chambers), PPC-05 (2), PPC-40 (2).

Absorbed dose-to-water calibration coefficients, $N_{D,w}$, are obtained in cobalt-60 and 6, 10, and 25 MV beams from NRC's Elekta *Precise* clinical linear accelerator ($\%dd(10)_x = 67.2\%$, 72.6%, and 84.4%, $\mathrm{TPR}^{20}_{10} = 0.681$, 0.731, and 0.800). The calibration procedure employs an indirect comparison with the Canadian primary standard for absorbed dose through laboratory maintained NE2571 reference chambers calibrated directly against the NRC primary standard water calorimeter. Absorbed dose calibration coefficients are then obtained for plane-parallel chambers with

$$N_{D,w,pp} = N_{D,w,\mathrm{ref}} \frac{M_{\mathrm{ref}}}{M_{pp}}, \tag{1}$$

where the fully corrected ion chamber readings, M, are measured close in time for the reference and plane-parallel chambers. The raw chamber reading is corrected using

$$M = M_{\mathrm{raw}} P_{TP} P_{\mathrm{leak}} P_{\mathrm{ion}} P_{\mathrm{pol}} P_{\mathrm{elec}} P_{rp}, \tag{2}$$

where the corrections to the reading are the same as TG-51 (Ref. 7) with the addition of the correction for variation in the radial intensity profile, P_{rp}, and obtained in the same way as in the work of McEwen.[14] The accuracy of this method of indirect comparison for calibrations was reviewed in detail in a previous publication.[16]

Measurements are performed in a $30 \times 30 \times 30$ cm^3 water phantom with the chamber centered on the axis of the horizontal beam. The measurement depth is 10.2 g/cm^2 for MV beams and 5.3 g/cm^2 for ^{60}Co irradiations including the entrance window of the phantom. These depths correspond to the depths at which water calorimetry is performed. For cylindrical reference chambers, the chamber is positioned with the centre of the chamber at the measurement depth. For plane-parallel chambers, the front face of the chamber is positioned at the measurement depth, then shifted upstream by the water equivalent thickness of the front face, obtained with physical densities. This places the front of the cavity at a water equivalent depth of 10.2 or 5.3 g/cm^2. These depths are different from the Monte Carlo simulations described below and when comparing results a shift is introduced to the measured results using the gradient of depth-dose curves resulting in a correction of up to 0.2%. The beam geometry is the same as that used by McEwen,[14] as are the electrometers, monitor chambers, and irradiation delivery. After obtaining $N_{D,w}$ coefficients, k_Q is calculated with

$$k_Q = \frac{N^Q_{D,w}}{N^{Co}_{D,w}}. \tag{3}$$

Chambers are preirradiated in linac beams to 1000 MU. To test chamber settling, no preirradiation is performed during cobalt-60 calibrations and readings are taken continuously until a stable reading is realized.

For each chamber, recombination measurements are made for at least three dose per pulse (D_{pp}) values, collecting data for a number of randomized applied voltages at each value. An initial Jaffé plot (1/reading vs 1/applied voltage) covering a wide range of polarizing potentials (300–30 V) was used to determine the maximum "safe" operating voltage where the plot showed a linear relation between 1/reading and 1/applied voltage. This applied voltage was then used for the calibration measurements described above. As has been shown by previous authors, and unlike cylindrical chambers, the "standard" applied voltage of 300 V is too high for many of the chamber designs. In general, the maximum applied voltage was 100–150 V. After obtaining the Jaffé plot, the recombination correction is determined through extrapolation to infinite voltage. For some chambers the initial component of ion recombination, taken as the intercept of the recombination correction as a function of dose per pulse, is up to 0.5%. However, it is generally

assumed that for continuous beams ($D_{pp} = 0$ Gy), the recombination correction is less than 0.1% and it is therefore not common practice to correct cobalt-60 calibration coefficients for ion recombination. For certain chambers investigated here, this would introduce an error of up to 0.5% in the determination of $N_{D,w}(^{60}\mathrm{Co})$ and, therefore, k_Q factors. Cobalt-60 recombination measurements are performed for a subset of chambers to compare with the results observed in pulsed beams using the intercept of the recombination correction as a function of dose per pulse.

The measurement uncertainty budget, common to all chambers, is derived according to the ISO Guide to Uncertainty in Measurement[17] and is provided in Table I. As reviewed above, it has been reported in the literature that chamber-to-chamber variation of k_Q factors for plane-parallel chambers of the same type are larger than for cylindrical chambers. Although this does introduce a minor component of uncertainty into the measured k_Q factors, chamber-to-chamber variability measured here is not as significant as suggested in previous publications and is discussed further in Sec. III.

II.B. Monte Carlo calculations: k_Q factors and uncertainties

Monte Carlo calculated k_Q factors are determined with the same approach used by Muir and Rogers,[9] whereby the equation

$$k_Q = \left(\frac{D_w}{D_{ch}}\right)^{Q}_{\mathrm{Co}}, \tag{4}$$

requires calculations of 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 a beam of quality Q to obtain k_Q. This equation assumes that $(\mathrm{W/e})_{\mathrm{air}}$ is independent of beam quality. A major difference between the simulations performed in this work and that of the previous publication[9] is that correlated sampling in the user code egs_chamber[18] is used for all calculations of the ratio $\frac{D_w}{D_{ch}}$ here. As discussed in our previous publication,[9] the effect of using correlated sampling is to reduce the relative statistical uncertainty without affecting the results obtained.

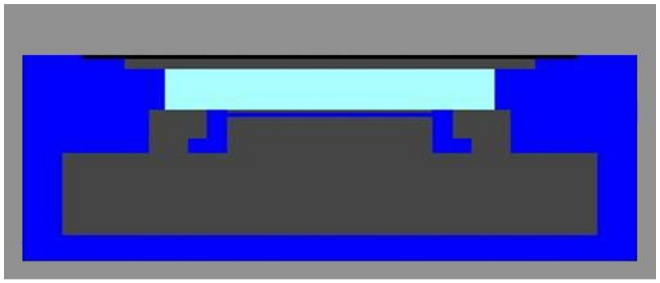
The simulation geometry is the same as in our previous publication.[9] Chambers are modeled using information from the manufacturers—Exradin provided detailed blueprints while PTW and IBA provided chamber drawings—as well as information from the literature. The NACP chamber model is modified using the graphite density for the front wall from the publication by Chin[19] where a chamber was sacrificed to determine more accurate specifications than had been provided by the manufacturer. Figure 1(a) provides an example Monte Carlo geometry for the IBA NACP-02 chamber. The simplified chamber model in Fig. 1(a) was modeled before drawings were obtained from IBA. Radiographs of the chambers are taken from the side and front of the chamber to ensure that the chamber drawings corresponded to the manufactured chambers and to aid with modeling the chambers. An example image of a scanned radiograph for the IBA NACP-02 chamber is given in Fig. 1(b). Chamber specifications are given in Table II. The PTW Roos chamber is modeled with PTW drawings but specifications from Zink and Wulff[20] are also used. The chamber is modeled with the front of the active collecting volume—the inside of the window—at the reference depth (5 cm for cobalt-60 and 10 cm for MV beams) with no shift for water equivalence. This gives k_Q factors consistent with how they are used in TG-51. Photon beams are modeled using the same photon spectra as the previous work[9] with $\%dd(10)_x$ ranging between 62.7% and 86.1%. Calculated k_Q factors are fit to the form

$$k_Q = a + b \times \%dd(10)_x + c \times (\%dd(10)_x)^2. \tag{5}$$

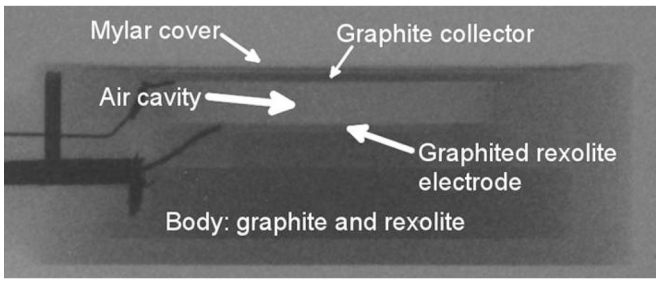
The fit is valid for $\%dd(10)_x$ between 62.7% and 86.1%. These spectra represent filtered beams; to investigate the

TABLE I. Combined uncertainty in measured $N_{D,w}$ coefficients and k_Q factors for plane-parallel ion chambers.

	Source	$N_{D,w}$ (%)	k_Q (%)
Type A			
1	Reproducibility in chamber reading (R/MU)	0.04	0.04
2a	Transfer of monitor calibration (NRC reference)	0.07	0.07
2b	Standard deviation of reference chamber calibration	0.05	0.05
3	Chamber-to-chamber repeatability	—	0.11
4	Long-term stability	0.36	0.19
Type B			
5	Uncertainty in NE2571 standard	0.34	0.27
6	P_{ion}	0.05	0.05
7	P_{pol}	0.08	0.08
8	P_{rp}	0.05	0.05
9	P_{leak}	0.01	0.01
10	P_{TP}	0.05	0.05
11	Chamber positioning	0.06	0.06
Combined uncertainty		0.52	0.45



(a)



(b)

FIG. 1. The IBA NACP-02 geometry. Figure 1(a) is the Monte Carlo model of the chamber while Fig. 1(b) is a radiograph of the chamber taken for aid with modeling and to ensure no significant differences between design and manufacture. Major components of the ion chamber are labeled in the radiograph of Fig. 1(b).

dependence of filtration on k_Q factors, k_Q is calculated for six unfiltered spectra covering the entire range of energies above for the IBA NACP-02 and Exradin A10 chambers. The Exradin A10 chamber is used because it employs steel screws to fasten the window to the chamber body and this may cause differences from calculations with filtered spectra, given the effects of a high-Z central electrode on k_Q factors[21] for cylindrical chambers.

Uncertainties in calculated k_Q factors are estimated in a similar manner to that from the previous publication.[9] Uncertainty from variation in stopping powers are introduced by varying the mean excitation energy, I, according to ICRU-37 (Ref. 22) uncertainty estimates ($k = 1$). Photon cross-sections are assumed to be correlated, introducing a negligible component of uncertainty into k_Q factors. Uncertainty from potential variable chamber dimensions is introduced by varying the collector spacing, the thickness of the front window materials and the guard width. For a subset of chambers, calculations of k_Q are performed with a BEAMnrc model as the source to test the use of photon spectra for the source input.

III. RESULTS AND DISCUSSION

III.A. Chamber stabilization

For most of the chambers investigated, settling time to within 0.05% of the mean of the last seven readings in the cobalt-60 reference field is less than six minutes. McCaffrey *et al.*[23] indicate that for well-guarded cylindrical chambers settling time is on the order of 9 min and this is consistent with the results observed here. None of the chambers investigated require longer than 15 min to achieve a stable reading. The chambers that take longer to settle are the PTW Markus and IBA PPC-05 chambers which employ a relatively smaller volume. McEwen[14] also noted that small volume cylindrical chambers take the longest time to settle (although the settling times for those chambers are significantly longer than those observed here). For most cylindrical ion chambers, the chamber reading starts high and is reduced—"settles"—as the chamber is irradiated but for most of the parallel-plate chambers the behavior is opposite; the reading starts low and increases. McEwen *et al.*[24] (measuring in electron beams) observed the opposite effect for the NACP chamber but their Markus chamber reading increased to equilibrium as observed here.

In linac beams, with a higher dose rate than the cobalt-60 beam, chamber settling is much faster. In these beams, the chambers are simply preirradiated to 1000 MU before calibration. However, for polarity and recombination corrections, readings are taken consecutively, typically for less than 3 min after the voltage is changed to ensure that the reading has stabilized before data are used for the Jaffé plots.

III.B. Leakage currents

Leakage current is measured immediately following chamber irradiation to obtain a measurement of radiation-induced leakage.[25] During initial chamber calibrations in the winter of 2011, all leakage readings contributed less than 0.05% to the measurement with radiation present. For most chambers, leakage contributes only about 0.01% to the reading when radiation is present so no correction for leakage is applied. The Exradin P11TW chamber with a large volume (0.92 cm^3) gives significant leakage readings (130 fA) but because of the large volume the measured signal is much larger than other chambers and the leakage contributes only 0.01% to the signal when measuring dose. Compare this to a chamber with a volume 18 times smaller which gives a leakage reading of 8 fA (16 times smaller) but contributes 0.02% to the signal. In addition, one can compare the result for the large volume plane-parallel chamber to the Farmer chambers measured by McEwen[14] which gave leakage currents between 20 and 30 fA. This is less than 1/4 of the leakage current for the P11TW but the Farmer chambers are only slightly smaller in volume.

In the summer of 2011, during measurements on the long-term stability of calibration coefficients, several ion chambers exhibited unexpectedly large leakage currents, typically 10–20 times larger than previously measured. Using an environmental enclosure it was found that for some chambers the leakage was directly dependent on the relative humidity—at low relative humidity values (~25%) leakage was around 10 fA, increasing to >300 fA at relative humidity ~60%. The process was reversible but the mechanism is unclear. Not all chambers behaved so predictably, others showed a step-change behavior, which means that it is more difficult to quantify the true leakage during calibration measurements. However, these strange effects were only seen at high relative humidity levels and, since all the calibration measurements used to determine experimental k_Q factors were obtained during periods of low relative humidity, we believe

TABLE II. Major dimensions and materials for the plane-parallel ion chambers investigated. The radius of the active region of the chamber is indicated with the total radius (active and guard region) in parentheses. Unless otherwise indicated, the density of graphite used for the Monte Carlo calculations is 1.7 g/cm^3. Materials are MYLAR, graphite (Gr), rexolite (cross-linked polystyrene, Rex), polyetheretherketone (PEEK), air-equivalent plastic (C552), polyoxymethylene (POM, trade name Delrin), polystyrene-equivalent plastic (D400), Kapton, and polyethylene (PE). The abbreviation Gr'd refers to a graphited material where a thin layer of graphite is applied to the material in question. Chambers indicated by an asterisk require a water-proofing cap.

		Cavity		Window			
Chamber	Volume (cm^3)	Depth (mm)	Radius (mm)	Material	Thickness (mm)	Wall materials	Collector
Exradin							
A11	0.622	2	9.9 (15.7)	C552	1	C552/POM	C552
P11	0.622	2	9.9 (15.7)	D400	1	D400/POM	D400
P11TW*	0.920	3	9.9 (14.3)	Kapton	0.03	D400/POM	D400
A10*	0.050	2	2.8 (7.3)	Kapton	0.03	C552/POM	C552
IBA							
NACP-02	0.157	2	5 (8)	MYLAR Gr (2.25 g/cm^3)	0.1 0.5	Gr/Rex	Gr'd/Rex
PPC-05	0.039	0.5	5 (8.5)	C552	1	C552/MYLAR	Gr'd/PEEK
PPC-40	0.402	2	8 (12)	Gr'd/PMMA	1	PMMA	Gr'd/PMMA
PTW							
Roos	0.384	2	7.8 (12)	Gr'd/PMMA	1.1	PMMA	Gr'd/PMMA
Markus*	0.044	2	2.7 (3)	PE	0.03	PMMA	Gr'd/PMMA
Advanced Markus*	0.020	1	2.5 (4.5)	PE	0.03	PMMA	Gr'd/PMMA

that leakage does not significantly affect the results presented here. However, these measurements indicate that (a) leakage is potentially more of an issue for parallel-plate than cylindrical ion chambers,[14] and (b) parallel-plate chambers may be more sensitive to higher levels of relative humidity as discussed further in Sec. III G.

III.C. Polarity correction

Table III provides the results for polarity corrections determined with the relation provided in TG-51.[7] Results in linac beams are combined for all energies investigated as the polarity correction is energy independent.[14,26] The standard deviation given in Table III is that for the combined polarity corrections from different energies and in some cases different experimental arrangements (for example, smaller SSD to obtain higher dose per pulse values for recombination). The low values of standard deviation in Table III further confirm energy independence of the polarity correction. The standard deviations in Table III are the average of the standard deviations of the polarity correction for all chambers of each type if more than one chamber is investigated. The largest value of standard deviation among the chambers is used as the uncertainty in the polarity correction in Table I. The largest correction to the reading is 0.29% for the Exradin A10 chamber. This is much larger than for well-behaved cylindrical chambers but not quite as large as for poorly behaved microchambers.[14] McEwen *et al.*[1] indicate polarity corrections of about 0.3% for the NACP chambers investigated which agrees reasonably with our value of 0.19% and our 0.03% correction for Roos chambers is in reasonable agreement with their value of 0.1%. However, the NACP chambers used in that study were manufactured by Scanditronix and the two chambers investigated here that were manufactured during that time period gave polarity corrections of only 0.1%. This disagreement may reflect chamber-to-chamber variations of geometric details which will be discussed further in Sec. III F. The disagreement between the results of the two studies also indicates the importance of measuring

TABLE III. Measured polarity corrections in linac beams and standard deviation.

	P_{pol}	
Chamber	Mean	Standard deviation (%)
Exradin		
A11	0.9995	0.08
P11	0.9990	0.05
P11TW	0.9992	0.01
A10	1.0029	0.02
IBA		
NACP-02	0.9981	0.01
PPC-05	0.9993	0.04
PPC-40	0.9999	0.02
PTW		
Roos	0.9997	0.01
Markus	0.9991	0.05
Advanced Markus	0.9986	0.06

the polarity correction for the specific chamber with which measurements are being made.

III.D. Ion recombination

III.D.1. Ion recombination in pulsed beams

As discussed above, for each chamber, Jaffé plots (1/I vs 1/V) are used to extract the ion recombination correction at each D_{pp} value. Linear behavior is observed on the Jaffé plots for all chambers as long as a sufficiently low voltage is used. For plane-parallel chambers, as voltage is increased onset of nonlinearity is observed at a lower voltage (200 V for some chambers) than for cylindrical chambers. For this reason, the chambers are operated with an applied voltage between 100 and 200 V. Figure 2 shows the ion recombination correction as a function of dose per pulse when collecting positive charge with an applied voltage of 100 V for all of the ion chamber types studied here. In cases where more than one chamber of each type is investigated, a representative chamber is chosen for Fig. 2. The ion recombination correction is linear as a function of D_{pp} as predicted by theory.[27–29] The slopes of the linear fits to the data of Fig. 2 increase because of the decreased electric field with increasing plate separation which also agrees with theoretical predications.[27] These gradients are coefficients of general recombination, C_{gen}, in the formalism of Burns and McEwen,[29] and increase with the square of the plate separation. Finally, comparison of the correction for recombination obtained using the multivoltage and two-voltage methods are used to assign an uncertainty from P_{ion} in Table I.

The intercepts in Fig. 2 provide a measure of initial recombination. For some chambers, the intercept is unexpectedly high—up to 0.44% for the Exradin A10 chamber.

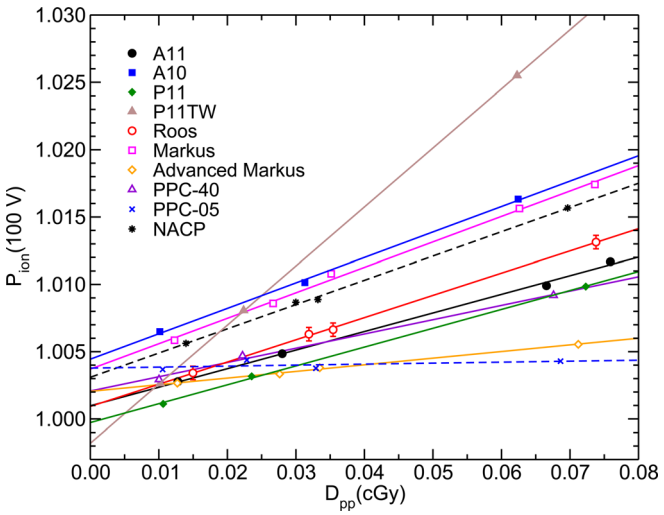


FIG. 2. Ion recombination correction factors as a function of dose per pulse for all chamber types collecting positive charge at an operating voltage of 100 V. Linear fits to the data are shown by lines. Most chambers use a plate separation of 2 mm and have very similar gradients in this figure except for the Exradin P11TW (3 mm), the PTW Advanced Markus (1 mm) and the IBA PPC-05 (0.5 mm). In cases where more than one chamber of each type was investigated, a chamber is used that is representative of the chamber type. Error bars representing systematic uncertainties are shown for the Roos chamber.

This unusual behavior prompted an investigation of the ion recombination correction for some chambers in cobalt-60 as discussed below in Sec. III D 3.

Most chambers exhibit expected recombination behavior when the polarity is reversed, like that shown by the NACP-02 chamber in Fig. 3. The gradients of the recombination correction as a function of D_{pp} are the same whether collecting positive or negative charge. However, two chambers—the PTW Advanced Markus and IBA PPC-05—exhibit strange behavior when the polarity is reversed. Figure 3 shows this behavior for one chamber of each of these types, although both chambers of each type exhibit similar unexpected behavior. The Advanced Markus has different recombination gradients when collecting opposite charge. The PPC-05 also shows different gradients and, when collecting negative charge, the recombination correction decreases as a function of D_{pp}. When investigating recombination behavior for cylindrical chambers, McEwen[14] observed anomalous recombination behavior for one scanning chamber and several microchambers. This behavior is not understood at this time but the two plane-parallel chambers that respond strangely also have small collecting volumes. This results in an increased electric field in these chambers which may be related to this anomalous behavior even though nothing is out of the ordinary with Jaffé plots for these chambers.

III.D.2. Comparison with literature values

The formalism of Burns and McEwen[29] is used to extract recombination parameters from Fig. 2 with

$$P_{\text{ion}} = 1 + (\gamma + \delta D_{pp})/U, \tag{6}$$

for comparison to published data. In the above equation, U is the applied voltage, γ is related to initial recombination and δ is related to general recombination. For plane-parallel

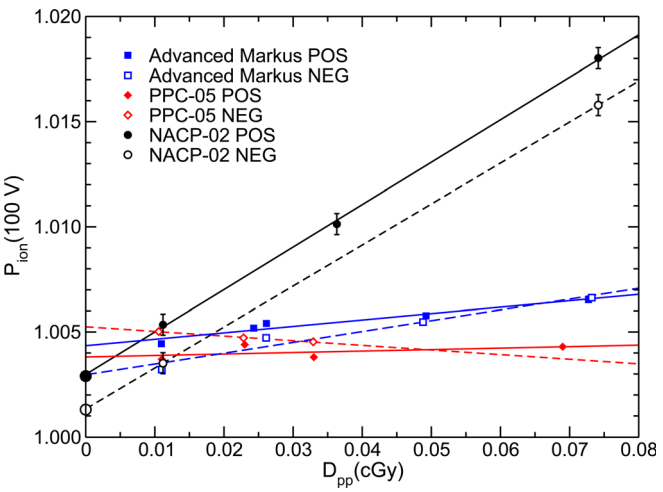


FIG. 3. Ion recombination correction factors as a function of dose per pulse showing the difference in recombination behavior depending on the polarity of the charge collected for some chambers. Solid symbols (solid lines) are data (linear fits) obtained when positive charge is collected while open symbols (dashed lines) are for negative charge collection. Error bars representing the systematic uncertainty in P_{ion} values are shown for the IBA NACP-02 chamber. Values of P_{ion} at $D_{pp} = 0$ Gy are obtained in cobalt-60 but are not used for the linear fits.

chambers, δ is expected to be proportional to square of the plate separation, d^2. Relative δ values among the chambers are consistent with differences in chamber dimensions. Values for γ and δ are provided in Table IV along with values obtained from the literature.

Bruggmoser *et al.*[30] provide recombination parameters for the PTW Roos, Markus, and Advanced Markus and IBA PPC-40 and NACP-02 chamber types. Burns and McEwen[29] provide values for the IBA NACP-02 chamber while Berg and Noerrevang[31] provide data for the PTW Roos. Pearce *et al.*[32] give values for the PTW Advanced Markus. Bass *et al.*[33] provide values for IBA NACP-02 and PTW Roos chambers. Unfortunately, no literature values are available for any of the Exradin plane-parallel chambers in Table IV. The P11TW chamber gives a negative γ value caused by an intercept below unity for this chamber (see Fig. 2).

Values of δ for the Roos chamber are consistent with literature values but the value of γ obtained by Bruggmoser *et al.*[30] is lower than that obtained here. This difference may be caused by collecting oppositely charged particles. The values of Table IV are for positive charge collection and in this investigation, a smaller value of γ is almost always obtained when collecting negative charge. The γ-value agrees within uncertainties with that of Berg and Noerrevang.[31] Recombination parameters for the Markus chamber agree with those of Bruggmoser *et al.*[30] Values of γ and δ for the Advanced Markus are lower than those provided by Bruggmoser *et al.*[30] However, δ agrees with that from Pearce *et al.*[32] who observed variability in the γ value (with k_{init} between 0.1 and 0.3) depending on which chamber was used. Since the average of their values is used for comparison, it seems that the γ values do not agree but a larger uncertainty is clearly warranted for this value because of chamber-to-chamber variations. Both recombination parameters for the NACP-02 and PPC-40 obtained here are also lower than those provided by Bruggmoser *et al.*[30] but the value of γ for the NACP-02 from Burns and McEwen[29] is lower than that from this study. In summary, of eight values of γ and δ obtained from other publications where only a few chambers are investigated only one γ-value and four δ-values agree with the results obtained here. The differences in terms of γ might be due to a difference in the sign of the charge collected or could indicate that the component of initial recombination is sensitive to changes in chamber construction. The variation in δ-values is most likely another indication of chamber-to-chamber variability for plane-parallel chambers. Bass *et al.*[33] give average values for the slope and intercept of P_{ion} as a function of D_{pp} with standard deviation in the values for about 40 NACP-02 and Roos chambers. The results of that study are in agreement within uncertainties with the results obtained here. Using the averaged results of Bass *et al.*[33] gives $\delta/U = 2.46 \pm 0.49$ mGy^{-1} and $\delta/U = 1.78 \pm 0.14$ mGy^{-1} for NACP-02 and Roos ion chambers, respectively. These results agree with the δ values obtained here and give an indication of the variation of δ-values for these chambers—the NACP-02 chamber exhibits much more variability in recombination coefficients for different chambers of the same type. It is therefore not surprising that when only a few chambers of each type are investigated, as in this study and those compared to above, the results are in poor agreement.

TABLE IV. Measured recombination parameters with comparison to literature values. Uncertainties on γ and δ are estimated to be 17% and 8%, respectively.

	This study		Literature values	
Chamber	γ/U	δ/U(mGy^{-1})	γ/U	δ/U(mGy^{-1})
Exradin				
A11	0.10	1.4		
P11	0.16	0.2		
P11TW	−0.18	4.4		
A10	0.44	1.9		
IBA				
NACP-02	0.28	2.0	0.48	2.4[a]
			0.07	2.4[b]
			0.15	2.5[e]
PPC-40	0.17	1.1	0.07	1.5[a]
PPC-05	0.33	0.0		
PTW				
Roos	0.12	1.7	0.06	1.7[a]
			0.14	1.8[c]
			0.13	1.8[e]
Markus	0.24	2.0	0.32	2.0[a]
Adv. Markus	0.32	0.4	0.43	0.5[a]
			0.2	0.4[d]

[a]Bruggmoser *et al.*, 2007 (Ref. 30).
[b]Burns and McEwen, 1998 (Ref. 29).
[c]Berg and Noerrevang, 2004 (Ref. 31).
[d]Pearce *et al.*, 2006 (Ref. 32).
[e]Bass *et al.*, 2009 (Ref. 33).

III.D.3. Ion recombination in cobalt-60

It is commonly assumed that initial ion recombination in cobalt-60 affects the response of the chamber reading by less than 0.1% and is therefore insignificant and not accounted for during chamber calibration. However, initial recombination can be up to a 0.2% effect for cylindrical chambers and should be corrected for consistently in continuous and pulsed beams.[34] Other authors[35] have observed large initial components of recombination, up to 0.66%, for NACP chambers. Over the course of the measurements for this study, large intercepts are observed in plots like Fig. 2, indicating up to 0.5% effects from initial recombination.

Measurements are performed in cobalt-60 to obtain recombination corrections at $D_{pp} = 0$ Gy, giving a direct measure of initial recombination to compare to the intercepts of Fig. 2. A sample of eight chambers is investigated in cobalt-60 in the same manner as in pulsed beams, specifically choosing some chambers that have large intercepts as well as the P11TW which has an intercept below unity. For six of eight chambers, recombination measurements from Jaffé plots in cobalt-60 agree well within 0.1% with the intercept of Fig. 2 (including the P11TW chamber). The chambers that do not agree are different by up to 0.28% but are two chambers (IBA PPC-05 and PTW Advanced

Markus) that exhibit anomalous recombination behavior as discussed above. Figure 3 shows the recombination correction obtained in cobalt-60 ($D_{pp} = 0$ Gy) for an NACP chamber and the exceptional agreement with the intercept from pulsed beams. For consistency, all chamber readings used to obtain calibration coefficients in cobalt-60, and therefore k_Q factors, are corrected using the intercept from pulsed beams. As mentioned above, Derikum[34] suggests that consistent recombination corrections should be applied in continuous and pulsed beams. The same author provides three methods to evaluate the correction for initial recombination and show that they give the same results within 0.05%.[36] The results of the current investigation confirm that the intercept of P_{ion} vs D_{pp} from pulsed beams gives the same correction for initial recombination as measurements of recombination in cobalt-60 and can be used to correct the chamber reading in cobalt-60. These results confirm that ignoring the effects of ion recombination in cobalt-60 beams can lead to systematic errors and that for plane-parallel chambers these can be up to 0.5%. To use such chambers for reference dosimetry would require that ion recombination was measured and applied at the calibration laboratory as well as in the clinic. This has implications for dosimetry protocols and/or recommended calibration procedures.

III.E. Measured and calculated k_Q factors

Measured k_Q factors (adjusted to the same point of measurement as described in Sec. II A) are plotted in Fig. 4 with Monte Carlo calculated k_Q factors and literature values. Table V provides fitting parameters for Eq. (5) to Monte Carlo calculated k_Q factors. The adjusted measured k_Q factors are presented in Table VI. Only two previous publications measured k_Q factors for plane-parallel chambers in photon beams. McEwen *et al.*[1] provided k_Q factors for the IBA NACP-02 and PTW Roos chambers while Kapsch and Gomola[2] determined factors for the IBA PPC-05 and PPC-40. Measured k_Q factors must be further adjusted for comparison to literature values. To compare the present measurements with results from the National Physical Laboratory (NPL),[1] the present results are corrected using depth-dose data such that the k_Q factors are for the chamber positioned with the inside of the window placed at the reference depth accounting for the water equivalent thickness using the electron density of the window and not corrected for cobalt-60 recombination since NPL results did not include this correction. For comparison with the Physikalisch-Technische Bundesanstalt (PTB) results,[2] the present measurements are not corrected for cobalt-60 recombination but no shift of the present data is required since the water equivalent thickness of the window is determined using physical densities in this work and for the PTB results (private communication, 2011). In addition, the PTB results[2] used k_Q factors from TRS-398 (Ref. 8) as the reference data for the NE2561 chamber. Therefore, for consistency in comparing k_Q data, the PTB results are adjusted using the Monte Carlo calculated k_Q factors of Muir and Rogers[9] which differ by up to 0.5%.

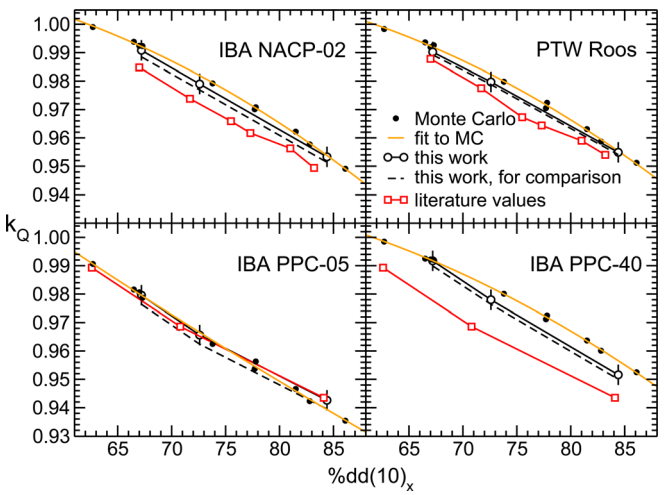


FIG. 4. Beam quality conversion factors with comparison to literature values and Monte Carlo calculations for the subset of chambers for which literature values are available. Filled symbols are calculated k_Q factors with a fit [Eq. (5)] to the values shown by the lightly colored line. Present measurements, shifted so that the inside of the chamber window is at the measurement depth and corrected for recombination in cobalt-60, are open circles with error bars representing combined systematic uncertainties. Measured literature values are shown by open squares, connected with straight lines. The dashed lines represent our measurements modified for comparison to literature values as described in the text. In the upper two panels, values are compared to measurements from McEwen *et al.* (Ref. 1). In the lower two panels, values are compared to k_Q factors measured by Kapsch and Gomola (Ref. 2).

TABLE V. Fitting parameters for Eq. (5) for k_Q in terms of $\%dd(10)_x$ and the rms deviation of the calculated data to the fit. The fit is valid for values of $\%dd(10)_x$ between 62.7% and 86.1%.

Chamber	a	b ($\times 10^3$)	c ($\times 10^5$)	RMS % deviation
Exradin				
A11	1.0658	−0.454	−1.029	0.07
P11	1.0231	1.123	−2.407	0.09
P11TW	1.0615	0.127	−1.820	0.08
A10	0.9799	1.656	−2.086	0.06
IBA				
NACP-02	0.9772	2.176	−2.907	0.04
PPC-05	1.1691	−3.204	−0.572	0.09
PPC-40	0.9891	1.699	−2.470	0.04
PTW				
Roos	0.9710	2.259	−2.896	0.07
Markus	0.9519	2.743	−3.114	0.06
Advanced Markus	0.9587	2.501	−2.974	0.06

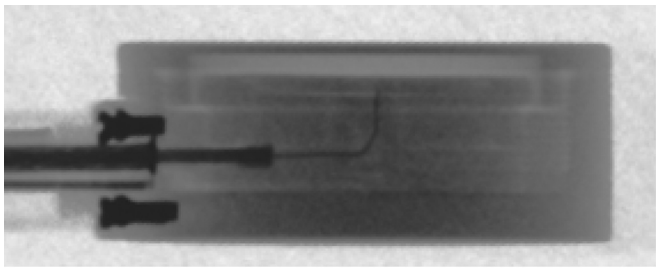
For almost all data points of Fig. 4, measured results are in agreement within systematic uncertainties with the fit to Monte Carlo calculated k_Q factors. Comparison between calculations and measured results is discussed further in Sec. III I. The combined uncertainty is 1.0% for k_Q factors from McEwen *et al.*[1] for the NACP-02 and Roos chambers. Although Fig. 4 shows that the results of this study are systematically higher than those from the NPL,[1] the values still agree well within systematic uncertainties. The systematic differences of about 0.5% between the two studies are present for both chambers indicating that the difference could result from measurements in the cobalt-60 reference field. Results for the IBA PPC-05 are in very good agreement with the results of Kapsch and Gomola[2] as seen in Fig. 4. However, the results are different by up to 1% for the IBA PPC-40 chamber type. As with the NPL results for the NACP and

TABLE VI. Measured k_Q factors and percent difference between measured and calculated k_Q factors. These measured values are those shifted for comparison to Monte Carlo values such that the inside of the front face of the chamber is at the reference depth. Combined uncertainties on measured k_Q factors are 0.4%.

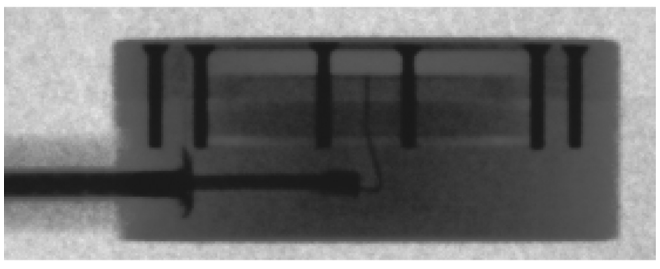
		6 MV	10 MV	25 MV	Percent difference		
Chamber	Number of chambers characterized	$\%dd(10)_x = 67.2$ $TPR_{10}^{20} = 0.681$	$\%dd(10)_x = 72.6$ $TPR_{10}^{20} = 0.731$	$\%dd(10)_x = 84.4$ $TPR_{10}^{20} = 0.800$	6 MV	10 MV	25 MV
Exradin							
A11	2[a]	0.9907	0.9803	0.9607	−0.19	−0.17	−0.66
P11	1	0.9916	0.9771	0.9504	−0.17	0.07	−0.42
P11TW	1	0.9879	0.9725	0.9473	0.00	0.25	−0.49
A10	1	1.0001	0.9913	0.9742	−0.32	−0.11	−0.32
IBA							
NACP-02	4	0.9908	0.9790	0.9533	0.14	0.30	0.05
PPC-05	2	0.9796	0.9656	0.9426	−0.01	0.10	−0.35
PPC-40	2	0.9917	0.9780	0.9516	0.01	0.43	0.52
PTW							
Roos	2	0.9902	0.9797	0.9549	0.19	0.28	0.04
Markus	2	0.9930	0.9807	0.9570	0.27	0.64	0.49
Advanced Markus	2	0.9936	0.9823	0.9595	−0.12	0.12	−0.17

[a]The two A11 chambers investigated had different geometric details since they were obtained before and after changes were made to chamber construction (see Fig. 5) so the k_Q factors provided here are for the newer model that is still available from Exradin.

Roos chambers, the differences are systematic. It is not understood how the results for one chamber type can agree but the other can be systematically different. This would indicate problems with one chamber type instead of differences in experimental procedures. The results of the investigation into the long-term stability of calibration coefficients (Sec. III G) would suggest that stability issues may partially explain the differences.



(a)



(b)

FIG. 5. Radiographs of Exradin A11 chambers showing major differences in body construction. Figure 1(a) is the older chamber model (S/N 145) which is no longer available for purchase while Fig. 1(b) shows the new chamber (S/N 81624) which is currently available from Standard Imaging.

The calculated results provided here are for spectra from filtered beams. Calculations of k_Q with spectra for six unfiltered beams over the range of energies investigated here agree within 0.2% with the fit to calculated values using filtered beams for both the NACP-02 and A10 ion chambers despite the use of steel screws for the A10 chamber construction. Additional calculations were performed using these spectra for unfiltered beams with the models of the cylindrical NE2571 and Exradin A12 chambers from our previous publication[9] and, again, the results are consistent with the fit to k_Q factors for filtered spectra within 0.2%.

There have been no publications to date that determine k_Q using Monte Carlo simulations for plane-parallel ion chambers in photon beams. However, Panettieri *et al.*[37] used the PENELOPE Monte Carlo code system to simulate chamber-quality factors, $f_{c,Q} = D_w/D_{ch}$, with cobalt-60 source models for IBA ion chambers which can be compared to the results from Monte Carlo simulations obtained in this study. Agreement with the results of that study is observed within 0.2%, 0.6%, and 0.2% for the IBA NACP-02 (using the same specification for the wall as that study), PPC-05 and PPC-40 chambers, respectively. This is reassuring given that different code systems and Monte Carlo models are used in each study. A discrepancy with Panettieri's NACP-02 results was observed by Wulff and Zink[38] using EGSnrc calculations. In the course of investigating, the differences between the three studies, we found that the specifications used for the electrode at the rear of the NACP-02 chamber are important and changes in these specifications can affect $f_{c,Q}$ by up to 0.5%. The results of the two code systems agree within systematic uncertainties when the same specifications are used as discussed by Wulff and Zink[38] and further in Sec. III H. The results obtained here agree with the result for $f_{c,Q}$ of Wulff and Zink[38] for the NACP-02 chamber (140 mg/cm^2 front wall and when using similar specifications for the back wall)

within 0.1%. Over the course of this analysis, several models of the NACP-02 chamber were made; the k_Q factors for the NACP-02 chamber provided in Table V are calculated using the model made from IBA chamber drawings.

III.F. Chamber-to-chamber variation of measured k_Q factors

Chamber-to-chamber variation of k_Q factors for plane-parallel chambers, specifically from variations in cobalt-60, has been discussed by several authors.[1–3,5,6,39] Some authors indicate variations of up to 4% in cobalt-60 (Ref. 3) related to the absorbed dose calibration factor, albeit for older chambers for which manufacturing processes were potentially variable or changing. Other studies such as that by Christ *et al.*[6] indicate that chamber-to-chamber variability is as low as for Farmer chambers.

In this study, it was possible to characterize more than one chamber for several chamber types. Two chambers were investigated for the Exradin A11, IBA PPC-05, and PPC-40, PTW Roos, Markus, and Advanced Markus and four chambers for the IBA NACP-02. Except for the NACP-02 and PPC-05 chambers, all k_Q factors for different chambers of the same type were within 0.2% of each other. This includes the two Exradin A11 chambers, which differ quite significantly in the construction of the outer body as shown in Fig. 5. Although this variation seems to be within the systematic uncertainty in k_Q factors given in Table I, the uncertainty on *relative* k_Q factors is actually only about 0.1% because some correlated uncertainties cancel. Therefore, the 0.2% variation observed in k_Q factors is outside of measurement uncertainties. The PPC-05 chambers have k_Q factors within 0.3% of each other. The NACP-02 chambers give k_Q factors which were up to 0.5% different from each other, although some chambers were manufactured by Scanditronix and some were provided by IBA. The standard deviation of the mean of the k_Q factors for the NACP-02 chambers was 0.11% in the 6 MV beam and this is what is assigned in Table I for uncertainty in k_Q factors from chamber-to-chamber variability. This is consistent with the standard deviation of the k_Q factors of Kapsch and Gomola[2] for several IBA chambers of types PPC-05 and PPC-40. When subsequent calibrations were performed to analyze long-term stability (Sec. III G), both chambers for three chamber types were investigated. Although the calibration coefficients and k_Q factors were different, the differences between chambers of the same type were consistent with the results discussed above. In summary, the large chamber-to-chamber variations reported in early investigations are not confirmed by recent measurements. Variations may be slightly larger than for reference-class cylindrical ion chambers but do not significantly affect the overall uncertainty in determining absorbed dose to water using a generic value of k_Q.

III.G. Long-term stability

Few authors report on long-term stability of calibration coefficients for plane-parallel chambers in photon or electron beams. Christ *et al.*[6] indicated no problems with long-term stability but without quantification. Palm *et al.*[5] indicate that the standard deviation of calibration coefficients for Roos chambers over a period of several months was 0.6%–0.7%. Bass *et al.*[33] report that for 20 NACP and Roos chambers the average repeatability of calibration coefficients is within 0.1%–0.2% but with some chambers giving repeat results that differ by up to 1%.

Long-term stability is investigated in this study by measuring calibration coefficients for a sample of chambers eight and eleven months after initial calibrations were performed in January 2011. Calibrations were also performed at both times for two Farmer-type chambers.

The cobalt-60 calibration coefficients for plane-parallel chambers obtained in August 2011, eight months following initial calibrations, are systematically lower by 0.6% on average (with 0.3% standard deviation) between calibrations while those for the Farmer chambers show no change within 0.1%. This is consistent with the stability results observed by Palm *et al.*[5] However, calibration coefficients for individual chambers were different by up to 1.2% after the eight month period between measurements. At the time of this recalibration, some chambers were behaving strangely in terms of leakage, as discussed in Sec. III B. These two factors may indicate a problem with the behavior of these chambers in cobalt-60 so calibrations were repeated in the 6 MV linac beam as well. Sixteen chambers were measured and, on average, calibration coefficients in the 6 MV beam only changed by 0.33% with a standard deviation of 0.46% and a maximum change of 1.5%. Better stability in 6 MV versus Co-60 may be due to the higher doserate of the linac beam (or pulsed versus continuous radiation). In addition, the average difference in k_Q factors over the eight month period is only 0.17%, again with a larger standard deviation than difference (0.28%) with a maximum change of 0.7%. An estimate of the type B uncertainty, using the mean difference and the root mean square deviation from zero, is assigned to $N_{D,w}$ coefficients for the chambers investigated and amounts to 0.36% in Table I. Likewise, uncertainty in k_Q factors in Table I is taken as 0.19%.

It became apparent over the course of this study that plane-parallel chambers might be more sensitive to variations in environmental conditions than cylindrical reference chambers. For this reason, calibrations were repeated in the 6 MV linac beam for at least one chamber of each chamber type eleven months following initial calibrations—at a time (December 2011) when environmental conditions were similar to those when the initial measurements were performed (January 2011). These measurements of calibration coefficients are much closer to the initial calibrations than those obtained at eight months (August 2011). On average, calibration coefficients were different by only 0.16% compared to the first set of calibrations from January 2011 with a standard deviation of 0.32%. Even the chamber for which calibration coefficients were different by 1.5% in August had a reduced difference from the initial calibration of 0.75%, still the maximum difference observed at the eleven month point. One factor that changes significantly at different times of the year but is not accounted for in the

measurements is variations in humidity. During January and December 2011, relative humidity was 25% but at the time of calibration in August it was much higher at 65%. These results clearly indicate that calibration coefficients are significantly affected by variations in relative humidity other than the well known effects on dosimetric quantities.[40]

It is clear that calibration coefficients for plane-parallel ion chambers are not as repeatable over long periods of time as cylindrical chambers, although it appears that k_Q factors might be. Values of k_Q factors reported in Table VI and Sec. III E use the original chamber calibrations; subsequent calibrations are only used to determine long-term repeatability of the measurements as reported above. More frequent monitoring of plane-parallel chambers, for example, using a Sr-90 check source as used by Bass *et al.*,[33] would seem to be required compared to cylindrical reference chambers. Alternatively, regular cross-calibration against a stable cylindrical chamber would achieve the same result. Although it is reassuring that measured k_Q factors appear to be stable, the use of parallel-plate chambers with TG-51 (Ref. 7) relies on the stability of $N_{D,w}(^{60}Co)$. Any variation in cobalt-60 performance, like that observed above, directly affects their ultimate use. The cross-calibration technique avoids these problems since the k_Q factors appear to be stable.

III.H. Systematic uncertainties in calculated k_Q factors

Systematic uncertainties in Monte Carlo calculated k_Q factors are investigated separately for each chamber type. Different chambers are made from various combinations of materials and geometric specifications so uncertainty in chamber simulations from stopping powers and chamber geometries must be determined separately. Table VII provides a sample uncertainty budget for the IBA NACP-02 chamber. All uncertainty calculations are performed for the Elekta SL25 25 MV spectrum.[41] For lower energy beams, uncertainty in k_Q factors will be less.[42] Relative statistical uncertainties on uncertainty calculations are generally less than 0.05% meaning that uncertainty contributions that are this low are not statistically significant and can be ignored.

Uncertainty in k_Q factors from uncertainty in material cross-sections is introduced by varying the mean excitation energy to introduce variation in electron stopping powers. Uncertainties in photon cross-sections are assumed to be correlated, introducing a negligible component of uncertainty in k_Q calculations.[9] Graphite stopping powers introduce the largest contribution to uncertainty in k_Q factors for the NACP-02, which is mostly made of graphite. Most other materials contribute an insignificant amount to the overall uncertainty. The combined uncertainty from stopping powers is 0.19% (Table VII).

Uncertainty in k_Q factors is introduced by varying the window thickness, collector spacing and guard width. The combined uncertainty from chamber dimensions is 0.19%. In Sec. III E, variations from using different mass thicknesses for the window of the NACP-02 chamber are indicated which impact k_Q factors by up to 0.3%. However, these changes in mass thickness are up to 26% and we assume that the graphite density for NACP-02 chambers is now known with increased certainty and that these sources of uncertainty are taken into account by the large variations of the thickness of the window materials in Table VII.

TABLE VII. Sample uncertainty budget for Monte Carlo calculated k_Q factors for the IBA NACP-02 chamber. Photon cross-sections are assumed to be correlated and contribute a negligible component to the uncertainty in calculated k_Q factors.

Source	Uncertainty in k_Q (%)
Stopping Powers (Vary I)	
Material (% Δ I)	
Mylar (5)	0.08
Rexolite (5)	0.02
Graphite (4.5)	0.16
Air (2.5)	0.04
Water (1.5)	0.04
Combined (Stopping powers)	0.19
Chamber dimensions	
Graphite window (±0.1 mm = 20%)	0.11
MYLAR cover (+0.1 mm = 100%)	0.02
Collector spacing (±0.3 mm)	0.10
Guard width (or r_{eff})	0.11
Combined (Dimensions)	0.19
Others	
Source model	0.06
Statistical uncertainty	0.06
EGSnrc[a]	0.10
Combined uncertainty without W/e	0.30
Updated uncertainty from W/e (Sec. III I)	0.25
Combined uncertainty	0.39

[a]Kawrakow, 2000 (Ref. 43).

Other sources contribute uncertainty to calculated k_Q factors. Relative statistical uncertainties in k_Q calculations are less than 0.1% (0.06% for the NACP-02 chamber). Another component of uncertainty is from the use of photon spectra instead of a full linac head or cobalt-60 irradiator simulation. Calculations of k_Q for the NACP-02 are affected by less than 0.06% when a full source model is used for the accelerator beam and cobalt-60 irradiator. Two other chambers (Exradin A11 and A10) were also used to determine the component of uncertainty from the simulated source and give slightly higher uncertainties in k_Q of up to 0.14%. An average of the uncertainty due to the choice of source model for the three chambers investigated is used as the uncertainty for all other chambers (i.e., 0.11%). EGSnrc has been shown to be accurate to within 0.1% relative to its own cross-sections for ion chamber calculations.[43]

Systematic uncertainties are combined by adding individual components in quadrature. Ignoring possible variation of $\frac{W}{e}$ with beam quality, this yields a systematic uncertainty of 0.30% for the NACP-02 chamber. Combining this with the uncertainty from possible variation of $\frac{W}{e}$ with beam quality of 0.25% (Sec. III I) gives a final combined uncertainty of 0.39% in k_Q factors for the NACP-02 chambers.

TABLE VIII. Combined uncertainty in Monte Carlo calculated k_Q factors. Uncertainty in calculated k_Q factors from possible variation in W/e is assumed to be 0.25% as estimated in Sec. III I.

Chamber	Combined uncertainty without W/e	Combined uncertainty with W/e component
Exradin		
A11	0.36	0.44
P11	0.43	0.50
P11TW	0.40	0.47
A10	0.32	0.41
IBA		
NACP-02	0.30	0.39
PPC-05	0.37	0.45
PPC-40	0.24	0.34
PTW		
Roos	0.24	0.34
Markus	0.32	0.40
Advanced Markus	0.34	0.42

Uncertainties in k_Q factors for other chamber types are investigated in much the same way. The combined uncertainty is given for all chambers with and without the component from variation of $\frac{W}{e}$ with beam quality in Table VIII. Uncertainties amount to between 0.34% and 0.50% depending on the chamber model. These values are similar to uncertainties in calculated k_Q factors for cylindrical chambers.[16]

III.I. Comparison of measured and calculated values

Figure 4 shows the excellent agreement between measured k_Q factors and the fit to Monte Carlo calculated values for the subset of chambers shown. Table VI shows the percent difference between measurements and calculations for all chambers investigated. Only three data points disagree by more than 0.5%. Figure 6 provides a histogram showing the distribution of chambers with given percent difference values; this shows the excellent agreement of the two data sets but indicates possible systematic differences with increasing energy. Average percent differences are −0.02%, 0.18%, and −0.16% for 6, 10, and 25 MV beams with standard deviations about the means of 0.17%, 0.23%, and 0.39%, respectively. Percent RMS deviations from zero are 0.17%, 0.29%, and 0.40% for the 6, 10, and 25 MV beams, respectively, with a % RMS deviation of 0.31% for the entire data set (all energies). These results indicate generally lower Monte Carlo calculated k_Q factors in the highest-energy beam with a 1.2% spread in the differences. In addition, in the high-energy beam all of the Exradin chambers have calculated k_Q factors systematically lower than measured values. This is the same trend as that for cylindrical chambers[16] even though the geometries for Monte Carlo calculations with the plane-parallel chambers are independently modeled and very different from the cylindrical chambers.

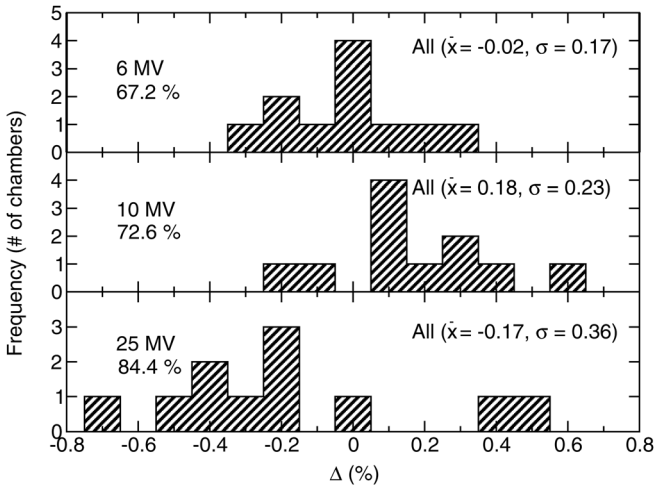


FIG. 6. Histograms showing the percent difference between measured and calculated k_Q factors for the 6, 10, and 25 MV beams.

Potential variation in $\frac{W}{e}$ can be investigated in the same manner as that used in our previous publication,[16] that is to assume that Eq. (4) includes an extra factor

$$\alpha = \left(\frac{W}{e}\right)_{Co}^{Q}. \tag{7}$$

Then, χ^2 is calculated as a function of α for the 25 MV beam to obtain the most probable value of α and uncertainty bounds. Performing this analysis with plane-parallel chambers yields $\alpha = 1.0012 \pm 0.0017$. As in the previous publication,[16] we assume that α is normally distributed to obtain an upper limit on $\left(\frac{W}{e}\right)_{\mathrm{Co}}^{25\mathrm{MV}}$ as 1.0020, 1.0034, and 1.0040 with 68%, 90%, and 95% confidence, respectively. The small sample of chamber types indicates that the assumption that α is normally distributed might be a poor one and the uncertainty on the value of α is slightly higher compared with that obtained for cylindrical chambers ($\alpha = 1.0024 \pm 0.0011$) (Ref. 16) but overall the values are in good agreement. The results of the two studies are consistent in terms of percent difference for the 25 MV beam and the value of α. This is impressive since the experimental method[14] required some modifications to adapt it to plane-parallel chambers and all Monte Carlo models are very different from those used for cylindrical chambers.[9] Performing the same analysis with the entire data set, including plane-parallel and reference-type cylindrical ion chambers, a value of $\alpha = 1.0021 \pm 0.0009$ is obtained giving our best estimate of the upper limit of $\left(\frac{W}{e}\right)_{\mathrm{Co}}^{25\mathrm{MV}}$ as 1.0025, 1.0033, and 1.0036 with 68%, 90%, and 95% confidence, respectively. This best estimate at the 68% confidence level is used to assign an uncertainty from possible variation of W/e with beam quality in Monte Carlo calculated k_Q factors in Tables VII and VIII.

IV. CONCLUSIONS

Measurements of calibration coefficients in cobalt-60 and linac photon beams allowed an analysis of the suitability of plane-parallel chambers for reference dosimetry. These chambers did not perform as well as cylindrical Farmer-type chambers in high-energy photon beams. Two of ten chamber types demonstrate recombination behavior which is not explainable with theory. Chamber-to-chamber variations in k_Q on the order of 0.2% were observed for chambers of the same type. The repeatability of calibration coefficients over

an eight month period was not satisfactory even though k_Q factors remained consistent. Given the instability of the plane-parallel chamber calibrations with time, it is recommended that cross-calibration is performed for both electron and photon beams each time plane-parallel chambers are needed after a period without being used.

Monte Carlo calculated k_Q factors are obtained for the chambers investigated. Systematic uncertainties for calculated results amount to between 0.34% and 0.50% depending on the chamber model. This is similar to that obtained for cylindrical chambers (0.40%–0.49%).[16]

Excellent agreement is observed between measured and calculated k_Q factors—average percent differences are −0.02%, 0.18%, and −0.16% with standard deviations of 0.17%, 0.23%, and 0.39% for 6, 10, and 25 MV beams, respectively. The χ^2/df for the entire data set is 0.3 which suggests that the uncertainty estimates are reasonable or possibly conservative. The upper limit of variation of W/e with beam quality is investigated in the same manner as our previous publication[16] and amounts to 0.20%, 0.34%, and 0.40% with 68%, 90%, and 95% confidence, respectively. This amount of variation is lower than that obtained in the previous work.[16] However, fewer chambers and chamber types were investigated here and the analysis yields a higher uncertainty. The combined data set consisting of plane-parallel and reference cylindrical ion chambers is used to obtain a best estimate of the upper limit on the variation of W/e with beam quality between ^{60}Co and 25 MV as 0.25%, 0.33%, and 0.36% with 68%, 90%, and 95% confidence, respectively.

Based on an objective assessment of chamber performance it is not possible at this time to recommend the use of plane-parallel ion chambers (as a class) for the reference dosimetry of high-energy photon beams. Individual chambers of specific types may achieve the performance comparable with a cylindrical reference-class ion chamber but the results obtained here suggest that increased monitoring of chamber stability is required (particularly where relative humidity can vary significantly). This conclusion does not affect the local use of plane-parallel chambers for relative dosimetry or via a cross-calibration against a stable cylindrical chamber (as in some electron dosimetry protocols).

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