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Evidence for using Monte Carlo calculated wall attenuation and scatter correction factors for three styles of graphite-walled ion chamber

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Abstract

The basic equation for establishing a ^{60}Co air-kerma standard based on a cavity ionization chamber includes a wall correction term that corrects for the attenuation and scatter of photons in the chamber wall. For over a decade, the validity of the wall correction terms determined by extrapolation methods (K_wK_{cep}) has been strongly challenged by Monte Carlo (MC) calculation methods (K_{wall}). Using the linear extrapolation method with experimental data, K_wK_{cep} was determined in this study for three different styles of primary-standard-grade graphite ionization chamber: cylindrical, spherical and plane-parallel. For measurements taken with the same ^{60}Co source, the air-kerma rates for these three chambers, determined using extrapolated K_wK_{cep} values, differed by up to 2%. The MC code 'EGSnrc' was used to calculate the values of K_{wall} for these three chambers. Use of the calculated K_{wall} values gave air-kerma rates that agreed within 0.3%. The accuracy of this code was affirmed by its reliability in modelling the complex structure of the response curve obtained by rotation of the non-rotationally symmetric plane-parallel chamber. These results demonstrate that the linear extrapolation technique leads to errors in the determination of air-kerma.

1. Introduction

A free air chamber used as a primary air-kerma standard (Attix 1986) can accurately measure air-kerma for photon beams of energy up to about 300 keV, after which the size of the free air chamber becomes impractically large, due to the range of electrons. For energies in the

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range of 300 keV to 3 MeV, primary air-kerma standards are based on cavity ion chambers and cavity theory. The basic equation for establishing a ^{60}Co air-kerma standard based on a cavity ionization chamber includes a wall correction term to correct for the attenuation and scatter of photons in the chamber wall,

$$K_{\mathrm{air}} = \frac{Q_{\mathrm{gas}}}{m_{\mathrm{air}}} \frac{(W/e)_{\mathrm{air}}}{(1-g)} \left[\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right]^{\mathrm{air}}_{\mathrm{gr}} \left[\frac{\overline{L}}{\rho}\right]^{\mathrm{gr}}_{\mathrm{air}} K_{\mathrm{h}} K_{\mathrm{wall}} K_{\mathrm{stem}} K_{\mathrm{an}} K_{\mathrm{comp}} K_{\mathrm{pol}} K_{\mathrm{sat}} K_{\mathrm{other}} \qquad (1)$$

where K_{air} represents air-kerma, Q_{gas} is the collected charge, m_{air} is the mass of dry air that would fill the chamber, $(W/e)_{\mathrm{air}}$ is the average energy deposited in dry air per unit charge released, g is the average fraction of a charged particle's energy lost via radiative events while slowing in air, $\left[\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right]^{\mathrm{air}}_{\mathrm{gr}}$ is the ratio of the mass-energy absorption coefficients of dry air to graphite, $\left[\frac{\overline{L}}{\rho}\right]^{\mathrm{gr}}_{\mathrm{air}}$ is the ratio of the mean restricted collision mass stopping powers of graphite to dry air, K_{h} is the correction factor for humidity (considered a constant as its value changes very little between a relative humidity of 15% and 60%), K_{wall} is a correction factor which corrects for attenuation and scatter in the wall (in extrapolation techniques, K_{wall} is given by the extrapolated K_{w} value multiplied by K_{cep} (centre of electron production)), K_{stem} corrects for the effect of stem scattering on chamber response, K_{an} is the axial non-uniformity correction factor, K_{comp} is the correction factor for any portions of the chamber made from different materials than the walls (i.e. insulators), K_{pol} is the polarity correction factor, K_{sat} corrects for incomplete ion collection in the air cavity, and K_{other} is the correction factor for other corrections specific to chamber types, used to compensate for the fact that an ionization chamber is not an ideal cavity.

In practice, the wall correction term is usually the largest and most significant correction applied in calculating a cavity ionization chamber response; it can be 1 to 3%. Traditionally, most standards labs determined K_{w} by an extrapolation method that involved adding additional wall thickness to ion chambers and linearly extrapolating the response vs wall thickness curve to determine the response for zero wall thickness. Another correction, K_{cep}, is also added to account for the centre of electron production (Cormack and Johns 1954, Boutillon and Niatel 1973) by removing the effect of photon attenuation and scattering in the graphite from the centre-of-production to the edge of the air cavity. Starting in the mid 1980s, with newly developed codes and faster computers, it was possible to calculate wall attenuation effects using MC techniques, where the calculated factor K_{wall} included K_{cep}. Rogers and Bielajew (1990) found that, although the MC codes could very accurately reproduce the response vs wall thickness curves, the calculated the values of K_{wall} were significantly different (up to 1%) from those determined by linear extrapolation in combination with K_{cep}. Based on a simple model which takes into account the varying wall thickness as seen from the beam direction from the centre to the edges of spherical ion chambers, Bielajew (1990a) showed that the extrapolation was, in fact, nonlinear for spherical chambers. Using this nonlinear extrapolation of the measured data led to reasonable agreement with the MC calculations. At the same time, Bielajew (1990b) also developed an analytic theory for K_{an} (the axial non-uniformity correction) to account for the fact that ion chambers are irradiated by a point source and not a parallel beam of photons. This theory demonstrated that the magnitude of correction was very small for ion chambers at about 100 cm from a source, and although this agreed with many standards laboratories, there were several labs for which this theory implied a substantial change.

Bielajew and Rogers (1992) also showed that the combination of the above corrections based on MC and analytic techniques would imply a 0.64% increase in the average air-kerma rate at six primary standards laboratories. In a more recent and detailed study using the EGSnrc

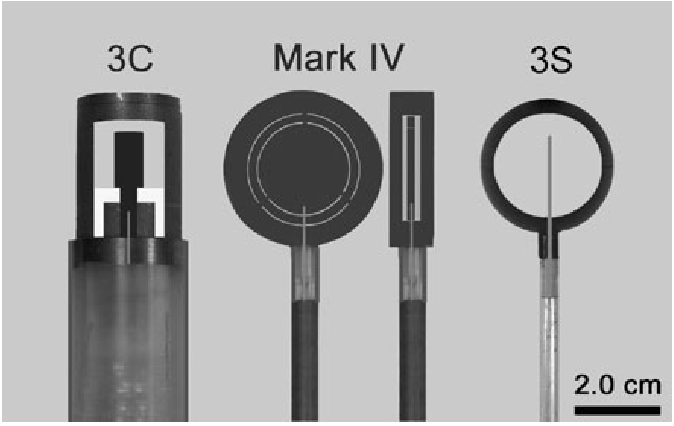

Figure 1. Three graphite-walled cavity ion chambers used in this study, with the interior air cavities illustrated (approximately to scale). The white inverted Ls in the 3C drawing represent the polystyrene insulator incorporated in this design. The 3S utilizes an aluminum electrode, while the other two chambers utilize graphite electrodes.

Monte Carlo code developed by Kawrakow (2000a, 2000b) which employs direct calculations rather than correlated scoring techniques, Rogers and Treurniet (1999) determined the average increase in air-kerma rate for 16 cavity standards at 14 primary standards labs would be 0.8%. This recent study showed that the MC curves duplicated extrapolation curves in the full build-up region. The present work is concerned with the consistency given by MC vs extrapolated K_{wall} correction factors. In the light of the earlier evidence, many standards laboratories are already considering switching to using MC calculated correction factors, and the present work supports this.

Other recent studies by Shortt *et al* (2002), Laitano *et al* (2002) and Büermann *et al* (2003) all provide evidence that the linear extrapolation technique is inadequate in measuring the wall correction factor. This present study provides clear evidence that MC calculations provide a more consistent and accurate value for the K_{wall} correction factor, and that linear extrapolation techniques used to derive K_w correction factors can introduce significant errors. The Monte Carlo code used in this study (EGSnrc) and its application to ion chamber modelling has been reviewed extensively in Kawrakow (2000a and 2000b).

2. Methods

To establish the validity of MC results for the K_{wall} correction factor, the CAVRZnrc and CAVSPHnrc user-codes of the EGSnrc MC code system were used to model three primary-standards-grade graphite cavity ion chambers: a large cylindrical chamber (3C; the Canadian primary standard), a plane-parallel chamber (the Mark IV), and a spherical chamber (3S), as illustrated in figure 1. A point source model of the incident beam and a spectrum that included all scattered photons was used for modelling the chambers. In addition, a phase space file from the BEAMnrc code (Rogers *et al* 1995) was used to calculate the response of the plane-parallel chamber.

The extrapolation method was also used to determine K_w values for the three styles of ion chamber, and these values of K_w multiplied by K_{cep} were compared with MC calculated K_{wall} values. Each of the three styles of ionization chamber consisted of an inner graphite chamber with a series of close-fitting sleeves, to allow measurements of a series of increasing wall thicknesses. Measurements of the effects of the build-up caps were performed using the NRC's Eldorado 6 ^{60}Co unit for all three chambers in this study, with the centre of each ion chamber positioned 1.0 m from the nominal front of the source capsule.

The 3C ionization chamber, which is the Canadian ^{60}Co primary exposure standard, was developed by W H Henry in the late 1950s. The 3C is a cylindrical graphite chamber with an outer diameter of 2.350 cm, an inner diameter of 1.584 cm, sidewall thickness of 0.383 cm and end cap thickness of 0.456 cm. This provides a total air volume of 2.7552 cm^3 for the 3C. The density of the graphite used in the manufacture of the chamber was 1.66 g cm^{-3}. All of the above 3C parameters are taken from Shortt and Ross (1986). More recently, the polystyrene end cap shown in white in figure 1 has been determined by MC calculations to have a significant effect (0.46%) on the 3C's response (Borg *et al* 2000, Rogers and Kawrakow 2003).

The extrapolated K_w correction factors for photon attenuation and scattering in the chamber sidewalls and end caps were determined by using the 3AS chamber, which has a cavity with similar dimensions to the 3C but with thinner sidewalls and end cap. Graphite sleeves of varying thicknesses were machined to fit over the primary sidewall of the 3AS, and the chamber response was measured as a function of wall thickness. These chambers, the extrapolation procedure and the MC-calculated K_{wall} factor are described in detail in Shortt and Ross (1986) and Rogers and Bielajew (1990). The historical extrapolated value for the wall correction factor K_w of the 3C includes two terms:

$$\begin{aligned} K_w &= K_{sw} K_{gc}{}^2 \\ &= 1.0245 \times 0.997\,32 \\ &= 1.0190 \end{aligned}$$

where K_{sw} is the correction due to the cylindrical sidewall of the chamber and $K_{gc}{}^2$ is the correction due to the graphite end cap plus the polystyrene base cap. To compare extrapolated K_w and MC-calculated K_{wall} values, the extrapolated K_w value must be multiplied by a K_{cep} term. In the case of the 3C, this value was estimated by Henry as $K_{cep} = 0.995$ (Shortt and Ross 1986), to give a combined $K_w K_{cep}$ value of 1.0139, with uncertainties of 0.2% and 0.08% for K_w and K_{cep}, respectively. The EGSnrc MC calculated K_{wall} value is 1.0220, which is 0.80% greater than the extrapolated value. The extrapolation lines and calculated values are shown in figure 2. Note that in this figure, the ~2 mm graphite thickness (~0.3 g cm^{-2}) values for both the end cap and the sidewall thicknesses do not fall near a line drawn through the other values, indicating that full build-up had not been achieved. These points were therefore not included in calculating the extrapolated value.

Takata *et al* have recently pointed out that the value of K_{wall} is sometimes very sensitive to the angle of the beam with respect to the ion chamber (Takata *et al* 2003a, 2003b). We have performed calculations for the 3C chamber and found that between 90° and 91° (angle is between the beam and the vertical axis of the ion chamber) the value of K_{wall} drops by 0.1% and the drop between 90° and 95° is about 0.20%, with a slight increase (0.05%) for angles between 85° and 90°. The asymmetry about 90 degrees is caused by the fact that the large electrode does not extend to the length of the cavity. If the electrode is extended to the top of the cavity in the calculations, the asymmetry disappears although there is still a small (0.05%) increase near 90°. With this sensitivity in mind, we determined that our accuracy in setting up the 3C chamber is better than 0.1 degree in the vertical. A 0.1 degree misalignment would mean that the distance to the source from the centre of the active volume at the top versus the bottom of the chamber would differ by 0.05 mm, and given the measuring accuracy of 0.01 mm (Allisy-Roberts *et al* 2000), it is not credible that there should be a larger misalignment.

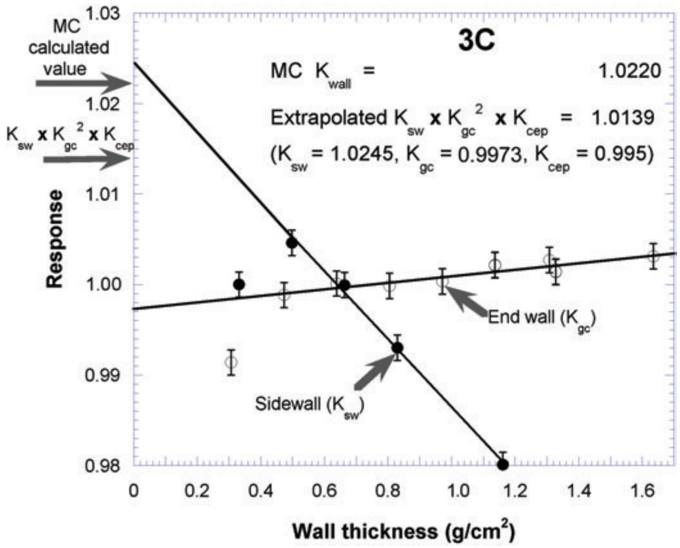

Figure 2. Plot of extrapolated values of K_w (where $K_w = K_{sw}K_{gc}^2$) for the 3C cylindrical ion chamber, where sw refers to the sidewall and gc represents the graphite end cap and polystyrene insulator base cap. The legend gives $K_w K_{gc}^2 K_{cep}$ (uncertainty of 0.2%) values compared with the Monte Carlo calculated K_{wall} values (uncertainty of 0.03%). The filled circles represent increasing sidewall thickness values and the open circles represent increasing end cap thickness values. Solid lines represent the extrapolations for the sidewall and end cap.

In the worst case this would lead to a 0.01% error in K_{wall}. This is ignored in the uncertainties considered below.

A series of graphite-walled plane-parallel ion chambers (Mark I to Mark V) were built in the 1970s by W H Henry to act as transfer chambers from dose-to-graphite to dose-to-water, and were based on a design by Boutillon and Niatel (1973). For the current study, we used the best characterized of these plane-parallel chambers (the Mark IV) and compared its response to that of the 3C. The Mark IV plane-parallel ion chamber is also made of graphite, with an outer radius 1.8 cm and thickness of 1.028 cm. The active collector is 0.201 cm thick with a radius of 1.077 cm, with front and back cavities 0.118 cm and 0.112 cm thick and an overall inner cavity radius of 1.347 cm. The front, back and sidewalls are 0.294 cm, 0.303 cm, and 0.454 cm thick, respectively. These values include the wall thicknesses of an inner 'bare' chamber, which does not have full build-up walls. The inner 'bare' chamber front and back walls are 0.0976 cm and 0.0997 cm thick, respectively and the sidewall is 0.20 cm thick. The 0.201 mm thick guarded central electrode is also graphite. The density of the graphite used in the manufacture of this chamber is 1.85 g cm^{-3}.

The volume of the Mark IV chamber was determined by a measurement of the capacitance of the chamber (a parallel plate capacitor with a guard ring), as described by Harris (1962). The factors other than mechanical dimensions that must be considered in guard ring capacitors are coplanarity of the guarded electrode and the guard ring, eccentricity of the guarded electrode with respect to the guard ring, flatness of the electrodes, parallelism of the guarded electrode and the high voltage electrode, effect of the width of the gap between the guarded electrode and the guard ring, and sufficient width of the guard ring to avoid fringing (Moon and Sparks 1948). The original capacitive measurement used for the volume of the Mark IV in 1981 gave a volume that was 0.32% larger than that calculated from the mechanical

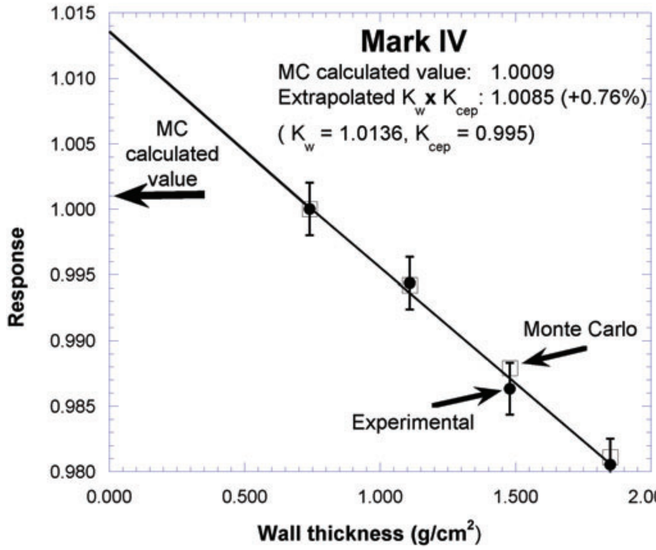

Figure 3. Plot of extrapolated values of K_w (uncertainty of 0.2%) for the Mark IV plane-parallel ion chamber. The solid line represents the extrapolation. The legend gives K_wK_{cep} values compared with the Monte Carlo calculated K_{wall} values (uncertainty of 0.03%). The filled circles and error bars represent the experimental values, and the open squares represent the MC calculations. The error bars on the MC calculations are smaller than the open squares.

dimensions recorded at that time. In this current study, the Mark IV air volume determined by the same capacitive method is 0.56% larger than the 1981 capacitive value. This change in volume could be accounted for by a 13 micrometer increase in the spacing between the central electrode and the front face of the chamber, presumably by swelling of the glue attaching the front wall cap. The back wall and sidewalls of the inner bare chamber of the Mark IV were designed as a cup, with a front wall cap that was glued into a notch in the sidewalls. Current measurements of the front-to-back dimension of the chamber compared to the historical values for this measurement show a small increase, in support of the view that this dimension has increased since the original (1981) measurements were made.

A series of graphite cups and caps were manufactured to fit around the bare Mark IV chamber. Historically, both the front and back wall thickness values used in the calculation of the extrapolated value of K_w included half the central electrode thickness (Boutillon and Niatel 1973, Henry 1972). The rationale for including half the central electrode thickness was that the full central electrode thickness functioned as a front wall for the back half of the air volume, and likewise, the full central electrode thickness functioned as a back wall for the front half of the air volume.

For the Mark IV, the 0° angle was defined as the flat face of the detector positioned perpendicular to the source. As shown in figure 3, the extrapolated value of K_w for the Mark IV plane-parallel chamber is equal to 1.0136. The K_{cep} value is 0.995 (Henry 1972). The K_wK_{cep} value of 1.0085 is 0.76% greater than the MC calculated value, and is in the opposite direction compared with the cylindrical and spherical chambers. The filled circles represent the measured values and the open squares represent the MC-calculated values in this figure.

The third ion chamber in this study, the 3S, was the third in a series of spherical chambers built to investigate the validity of the extrapolation method for the determination of K_w for a chamber irradiated in a ^{137}Cs beam. A detailed study of this chamber (Shortt *et al* 2002),

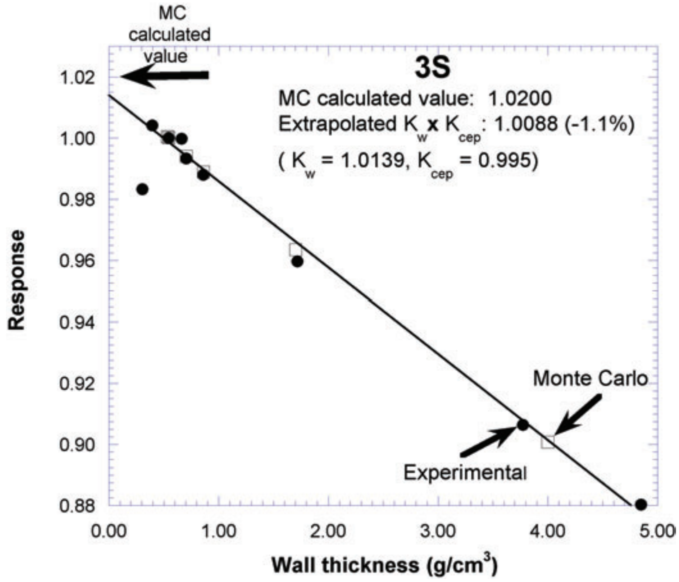

Figure 4. Plot of extrapolated values of K_w (uncertainty of 0.2%) for the 3S spherical ion chamber. The solid line represents the extrapolation. The legend gives $K_w K_{cep}$ values compared with the Monte Carlo calculated K_{wall} values (uncertainty of 0.03%). The filled circles represent the experimental values, and the open squares represent the MC calculations. The error bars for the experimental values are approximately the same size of the symbols, and for the MC calculations are a factor of 20 smaller than the symbols.

presents experimental verification of the nonlinearity of this ion chamber's response as a function of wall thickness in a ^{137}Cs beam. In the current study, all chambers including the 3S were irradiated by a ^{60}Co beam. An approach similar to that detailed in the study mentioned above could not be undertaken in ^{60}Co, because the nonlinearity, which is just measurable in the^{137}Cs beam, is very small over the range of wall thicknesses experimentally measurable in ^{60}Co. Thicker walls are required to produce charged particle equilibrium.

The 3S spherical ion chamber, described in detail in Shortt *et al* (2002), is constructed with graphite of density 1.78 g cm^{-3}. It has an inner diameter of 2.60 cm and has the largest volume of the three chambers in this study, at 9.1903 cm^3. The volume of the two hemispheres that comprised the spherical ion chamber was determined by the dimensional metrology group at NRC, using a Mitutoyo Legex 707 coordinate measuring machine. The central electrode of the 3S is a 1.0 mm diameter aluminium rod. The effect of the aluminium electrode has been modelled as a sphere of equal volume using the MC program CAVSPHnrc and shows negligible (0.045%) effect. CAVSPHnrc can only model spherically symmetric geometries. Therefore, in the model we inserted a sphere with the same volume as the cylindrical electrode since the number of photon interactions is proportional to the mass of the electrode. This approximation had the goal of gaining an impression of the magnitude of the electrode perturbation to the cavity dose. Note that using this same approach to calculate the electrode effect in a Baldwin–Farmer chamber gave good agreement with the more accurate geometry calculation.

Graphite hemispheres were constructed to fit over the top and bottom halves of the base chamber, allowing the extrapolation experiment to be performed. Figure 4 shows extrapolated data for K_w, plus the calculated MC K_{wall} value for this chamber. The additional point at

Table 1. Principle values used in calculations of the air-kerma ratios for three ion chambers. The second row for each chamber contains estimated uncertainties (quadratic summation of type A and type B) of the various quantities listed.

	Q_{gas} (nC)	V (cm^3)	K_{stem}	K_{an}	K_wK_{cep} extrapolation	K_{wall} Monte Carlo	K_{comp}	K_{pol}	K_{sat}	$\frac{K_w K_{cep}}{K_{wall}}$
Mark IV	0.53645	0.8587	0.9997	1.0015	1.0085	1.0009	1.000	0.9975	1.0015	1.0076
Uncertainty	0.10%	0.15%	0.02%	0.07%	0.2%	0.03%	0.01%	0.1%	0.1%	
3S	5.60852	9.1903	1.000	0.9991	1.0088	1.0200	0.9996	0.9995	1.0010	0.9890
Uncertainty	0.10%	0.15%	0.02%	0.06%	0.2%	0.03%	0.01%	0.1%	0.1%	
3C	1.67643	2.7552	0.9960	1.0004	1.0139	1.0220	1.0046	1.0006	1.0016	0.9921
Uncertainty	0.07%	0.09%	0.02%	0.06%	0.2%	0.03%	0.17%	0.1%	0.04%	

Table 2. Ratios of air-kerma rates of the Mark IV to the 3C and the 3S to the 3C, using extrapolated K_wK_{cep} values and MC-calculated K_{wall} values. The air-kerma rates for the 3C include the relevant correction factors for each ratio. Values in parentheses are the estimated uncertainties. The 3C is the Canadian primary standard reference chamber.

	With extrapolated $K_w K_{cep}$	With Monte Carlo K_{wall}
$\frac{K^{pp}}{K^{3C}}$	1.018 (0.4%)	1.003 (0.3%)
$\frac{K^{3S}}{K^{3C}}$	0.994 (0.4%)	0.997 (0.3%)

$\sim$0.3 g cm^{-2} wall thickness represents a point where full build-up is not achieved, and this value was not used in the extrapolation. The extrapolated value of K_wK_{cep} for the 3S is 1.1% less than the MC calculated K_{wall} value using $K_{cep} = 0.995$ from Bielajew (1990a).

For all three chambers, the extrapolated K_wK_{cep} value is significantly different from the MC K_{wall} values. For the plane-parallel Mark IV chamber, the extrapolated K_wK_{cep} value gives a +0.76% difference, the spherical 3S chamber a -1.10% difference, and the cylindrical 3C ionization chamber a -0.79% difference from the MC K_{wall} value (table 1). The values and uncertainties in table 1 are best estimates taken from Henry (1972–1980), Shortt and Ross (1986), Bielajew (1990a), Shortt *et al* (2002), Rogers and Kawrakow (2003), and measurements and calculations performed for this current study.

Table 2 presents the ratios of the air-kerma rates determined by using the extrapolated K_wK_{cep} values to those with the MC K_{wall} values for the Mark IV and the 3S relative to the 3C primary standard chamber. For both ratios, the MC-calculated values are much closer to unity than the extrapolated values, supporting the contention that the MC-calculated values for the three chambers are more accurate than the extrapolated values.

The accuracy of MC calculations is of critical concern in this current study. A verification of their accuracy can be done experimentally by performing a rotation experiment on the ion chamber that lacked rotational symmetry about its stem (the plane-parallel Mark IV). For this experiment, this chamber was rotated through 360° about its stem, and the response was measured as a function of angle. The expected response for this rotation was also calculated as a function of angle using the EGSnrc MC code. The chamber is symmetric by design, and the measurements in the four quadrants were very similar. The measured and experimental results are shown in figure 5, where the four quadrants of the rotation experiment (0–90°, 90–180°, 180–270° and 270–360°) were folded together, averaged, and plotted on the x-axis from 0° to 90°. A distinctive shoulder structure in the response curve over the 80–85° region of rotation is apparent for both the measured and calculated curves. This structure corresponds to the angle

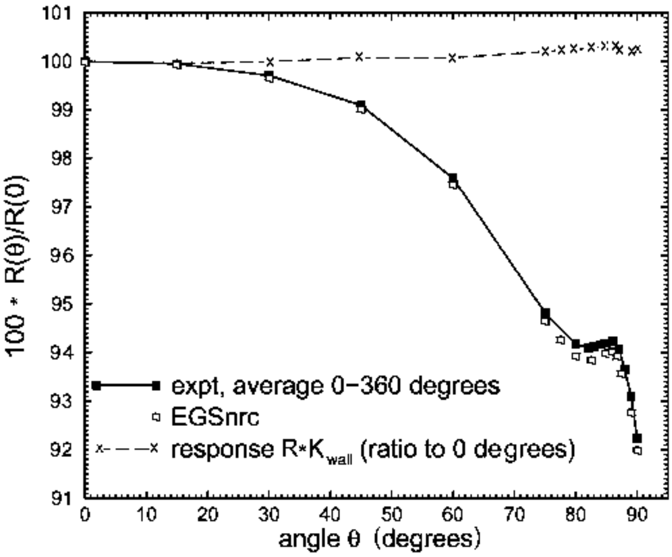

Figure 5. Measured versus calculated responses of the Mark IV plane-parallel chamber as a function of angle. All responses $R(\theta)$ are normalized to that at 0° $R(0)$. The MC responses (open squares—uncertainty of 0.1%) were calculated with the EGSnrc MC code. The measurements (black filled squares—uncertainty of 0.2%) were made at 100 cm and were taken in all four quadrants (0–360°), but collapsed to the 0–90° quadrant and averaged.

where the beam begins to enter the chamber through the curved sidewall. At approximately 85°, the beam axis begins to pass through the entire diameter of the central electrode. The unusual shape of this curve in the 80–90° region is based on the attenuation and geometry.

This unusual curve shape presents a significant opportunity to test the MC code's ability to respond to a difficult modelling problem. The calculations agree within 0.3% of the measurements, and reproduce the distinct shoulder structure. The fact that the calculated response multiplied by K_{wall} (× in figure 5) is close to constant and has a maximum difference of 0.3% close to 90° indicates that the 8% variation in response from 0° to 90° is almost entirely due to the attenuation and scatter in the chamber's walls. This result supports our confidence in the accuracy of the EGSnrc MC calculations of K_{wall}. The residual variation in the calculated response divided by K_{wall} was shown to be a point of measurement effect (variation of K_{an}), and disappears if a parallel beam is used in the calculation.

As a final confirmation of the MC code's ability to accurately compute the ion chamber's response, we have measured and calculated the response of the bare Mark IV ion chamber, i.e. without sufficient wall thickness for full build-up in a ^{60}Co beam. In all previous calculations we needed to consider only the photon component of the ^{60}Co beam, because of the walls were thick enough to stop all electrons from the source head. The thin walls of the bare chamber also required simulating the electron component of the ^{60}Co beam. This calculation was performed using the BEAM MC code and the model of the NRC ^{60}Co unit described by Mora *et al* (1999). By direct calculation it was found that the electrons contribute +3.9% to the response in the 0° position because of the thin front wall, but less than +0.05% in the 90° position, where the walls are thicker. The measured ratio of the bare chamber response to the full build-up chamber response was found to be in good agreement with the MC-calculated ratios of response. At 0°, the measured ratio is 0.906 ± 0.1% and the calculated ratio was also 0.906 ± 0.1%. At 90°, the measured ratio was 0.984 ± 0.1% and the calculated ratio was 0.980 ± 0.1%.

3. Conclusions

The largest and most significant correction applied in calculating a cavity ionization chamber's response in a ^{60}Co beam is the wall attenuation and scatter correction term. Shortt *et al* (2002), Laitano *et al* (2002) and especially Büermann *et al* (2003) provide convincing evidence that the linear extrapolation technique is inadequate in measuring the wall attenuation and scatter correction factor. In the current study we used the same 3S spherical chamber that was used in the Shortt *et al* (2002) study, as well as the cylindrical Canadian primary standard chamber (the 3C) and a primary-standards-grade plane-parallel chamber, the Mark IV. For the 3S spherical chamber, the MC results in this current study match in sign and are similar in magnitude to both the nonlinear fit and MC calculations reported by Shortt *et al* (2002). The nonlinear response measured in the Shortt *et al* (2002) study for a ^{137}Cs beam could not be reproduced in a ^{60}Co beam, since the region where the curvature becomes large enough to be measurable is not accessible because the wall thicknesses are below that required for full build-up.

The results presented here demonstrate that for three styles of ionization chamber (cylindrical, spherical and plane-parallel), the extrapolation procedures produce significantly different values for $K_w K_{cep}$ than MC calculations that produce the equivalent K_{wall} values. The MC-calculated values are shown to be more accurate as they provide more consistent values of the air-kerma rate measured with these three chambers. Further, MC calculations were sufficiently accurate to predict the subtle structure in the response curve of a rotated plane-parallel chamber. These results add confidence to the assessment of MC as the preferred method of determining K_{wall} corrections for ionization chambers used in ^{60}Co beams.

It is very satisfying that the two independent absolute determinations of the air-kerma rate in the NRC ^{60}Co beam both agree within uncertainties with the declared primary standard based on the 3C chamber, and the average air-kerma rate agrees with the 3C determination within 0.02%.

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