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Wall attenuation and scatter corrections for ion chambers: measurements versus calculations

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Abstract. In precision ion chamber dosimetry in air, the wall attenuation and scatter are corrected for by A_{wall} (k_{att} in IAEA terminology, K_w^{-1} in standards laboratory terminology). Using the EGS4 system we show that Monte Carlo calculated A_{wall} factors predict relative variations in detector response with wall thickness which agree with all available experimental data within a statistical uncertainty of less than 0.1%. However, our calculated correction factors for use in exposure and air kerma standards are different by up to 1% from those obtained by extrapolating these same measurements. Using calculated correction factors would imply increases of 0.7–1.0% in the exposure and air kerma standards based on spherical and large diameter, large length cylindrical chambers and decreases of 0.3–0.5% for standards based on large diameter pancake chambers. Calculations are also shown to agree within 0.05% with the measurements of Rocha and co-workers for clinical chambers. These experimental data are not in exact agreement with the γ values used in the AAPM protocol to obtain A_{wall}. However, the AAPM final values of A_{wall} agree within 0.2% with the more accurate values calculated here.

1. Introduction

Wall attenuation and scatter correction factors for ion chambers in air are used by standards laboratories to establish primary standards for exposure or air kerma in a ^{60}Co or ^{137}Cs beam. They are also used in clinical dosimetry protocols to determine the chamber calibration factors, N_D (IAEA 1987, NACP 1980, etc) or equivalently, N_{gas} (AAPM 1983). These factors correct the chamber's response for the attenuation of the photon beam in the wall of the ion chamber and for the contribution of scattered photons to the response of the chamber.

There are two main approaches for determining these correction factors. In one method, they are deduced by measuring the variation in ion chamber response as a function of wall thickness in the full build-up region, extrapolating to infer the response at zero wall thickness and then applying a theoretical correction factor to account for the effects of electron transport (see, for example, Loftus and Weaver 1974, Niatel *et al* 1974, Shortt and Ross 1986). This latter correction is needed because most of the energy deposited in an ion chamber's cavity comes from electrons which are set in motion upstream of the cavity. Most of the photons do not traverse the entire wall thickness thus reducing the effective attenuation. Details of how to make this correction are ambiguous. For example, for very similar pancake chambers, the

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corrections for the centre of electron production which are applied at the BIPM (the international standards laboratory in Paris) and at the PTB (the German standards laboratory) are 0.75±0.02% and 0.30±0.15% respectively (Niatel *et al* 1974). For cylindrical and spherical chambers the procedure for calculating this correction is even less clear. Nonetheless, all standards laboratories use the approach of combined measurements and calculations to determine the overall wall attenuation and scatter correction factors†.

Another approach is to use Monte Carlo calculations to simulate an ion chamber's response and to extract the relevant correction factors. Although calculations of ion chamber response to photons are extremely sensitive to details of the Monte Carlo simulation, the calculated correction factors are much less sensitive. There is agreement at the ±0.2% level between the three published reports which cover a wide variety of commercial chambers (Rogers *et al* 1985, Nath and Schulz 1981, McEwan and Smyth 1984). In particular, our present calculations for the BIPM pancake chamber and the NIST 1 cm^3 chamber agree with the calculations of Nath and Schulz, which have a statistical uncertainty of ±0.2%, as discussed in Rogers *et al* 1985. There is a rigorous theoretical justification for the methods of extracting these correction factors from the Monte Carlo calculations (Bielajew 1986). However, comparisons between the calculations and the extrapolated experimental data (which include the calculated correction for the centre of electron production) show disagreements of ±0.7% (Rogers *et al* 1985) despite statistical uncertainties of 0.2% or less.

As part of a re-evaluation of the correction factors used in the Canadian primary exposure standard (Shortt and Ross 1986), we have investigated this topic more closely. We have found that we can calculate, typically to within 0.1%, all the published experimental data on chamber response versus wall thickness for thicknesses larger than the minimum thickness to establish electron equilibrium; yet the large differences in the overall correction factors persist. This stimulated another investigation which showed that the extrapolation of chamber response to zero wall thickness is **non**-linear in spherical geometries, contrary to most currently used procedures (Bielajew 1990a).

In the next section we define some notation and discuss some improvements in our Monte Carlo code. We then present a detailed comparison of the Monte Carlo results to the high quality data measured in ^{60}Co beams at standards laboratories and explore the implications of these results on these standards. Most clinically used A_{wall} correction factors have been calculated assuming an idealised symmetrical build-up cap. Using some data from the IRD (the Brazilian standards laboratory (Rocha *et al* 1989)) we investigate the effects of using non-ideal build-up caps with clinical ion chambers.

2. Theory and calculations

2.1. Notation

The measured ionisation from a chamber with wall thickness t is proportional to $R(t)$, the absorbed dose to the gas in the cavity. For walls that are thick enough to establish

† The BIPM uses a unique approach which includes a calculated attenuation correction and a scatter correction determined by a quadratic extrapolation of measured responses less the calculated attenuation as a function of wall thickness (Boutillon and Niatel 1973). However, the net result appears to be mostly based on extrapolation of the chamber response to zero wall thickness.

charged particle equilibrium in the chamber's cavity, and assuming the normal tenets of cavity theory hold, one has

$$R(t) = K_{\mathrm{col,air}} s_{\mathrm{air,wall}} (\overline{\mu_{\mathrm{en}}}/\rho)^{\mathrm{wall}}_{\mathrm{air}} A_{\mathrm{wall}}(t) A_{\mathrm{oth}} \tag{1}$$

where $K_{\mathrm{col,air}}$ is the collision kerma in air at the geometric centre of the cavity in the absence of the chamber, $s_{\mathrm{air,wall}}$ is the stopping-power ratio (see, for example, Spencer and Attix 1955, ICRU 1984, Rogers *et al* 1985), $(\overline{\mu_{\mathrm{en}}}/\rho)^{\mathrm{wall}}_{\mathrm{air}}$ is the ratio of spectrum averaged mass-energy absorption coefficients in the wall to those in the air, $A_{\mathrm{wall}}(t)$ is the wall attenuation correction factor for this particular wall thickness, t, and A_{oth} groups several other small correction factors which are taken as independent of the wall thickness (stem, electrode and field non-uniformity effects (Bielajew 1990b)). The measured ionisation is assumed corrected to standard conditions. The walls are assumed to be of one material. In standards laboratories, this equation is used to determine $K_{\mathrm{col,air}}$ and hence the correction factors used are the inverses of the A, normally denoted by K or k. In contrast, the IAEA (1987) and NACP (1980) protocols both use the notation $k_{\mathrm{att}} = A_{\mathrm{wall}}$ and $k_{\mathrm{m}} = s_{\mathrm{air,wall}} (\overline{\mu_{\mathrm{en}}}/\rho)^{\mathrm{wall}}_{\mathrm{air}}$.

Since A_{wall} corrects for both attenuation (which decreases the response) and scattering (which increases the response), it can be either greater or less than unity. However, attenuation usually dominates so that A_{wall} is less than unity.

For comparison to measurement it is useful to consider two components of A_{wall}:

$$A_{\mathrm{wall}}(t) = A_{\mathrm{w}}(t) A_{\mathrm{cep}} \tag{2}$$

where $A_{\mathrm{w}}(t)$ is a wall-thickness-dependent correction factor which corrects the collision kerma in the cavity for the effects of attenuation and scatter in the walls and A_{cep} is the correction for the centre of electron product which is needed so that $A_{\mathrm{wall}}(t)$ corrects the absorbed dose to the gas (see, for example, Attix 1984). Bielajew (1986) has shown rigorously that Monte Carlo calculations which include electron transport calculate $A_{\mathrm{wall}}(t)$. Unfortunately, the AAPM 1983 protocol erroneously associated Monte Carlo calculated A_{wall} values with A_{w} (AAPM used the notation $A_{\mathrm{wall}}, \beta_{\mathrm{wall}}$ for our quantities $A_{\mathrm{w}}, A_{\mathrm{cep}}$). This error was corrected in the AAPM letter of clarification (Schulz *et al* 1986).

Note that A_{cep} corrects for a reduction in the effect of photon attenuation in the walls and hence by definition is a quantity greater than unity.

The experimental data available consist of a series of relative measurements of $R(t)$ (taken as the measured charge corrected to standard conditions) for different values of the wall thickness, t. These values are extrapolated linearly to determine $R(0)$ and then

$$A_{\mathrm{w}}(t) = R(t)/R(0). \tag{3}$$

To determine $A_{\mathrm{wall}}(t)$ from the measured value of $A_{\mathrm{w}}(t)$, a theoretical estimate of A_{cep} is used.

2.2. Monte Carlo calculations

The Monte Carlo calculations were done using the EGS4 code system (Nelson *et al* 1985) and an updated version of the users code CAVITY which was reported previously (Bielajew *et al* 1985). We have made the following enhancements:

(1) the PRESTA electron transport algorithm is used, thereby saving a factor of five or more in the CPU time (Bielajew and Rogers 1987);

(2) spherical chambers can be modelled as well as cylindrical chambers;

(3) the source routines were modified to use an input energy spectrum since nearly 30% of the photon fluence in a ^{60}Co beam is from scattered photons (the ^{60}Co spectrum from Rogers *et al* (1988) is used);

(4) different graphite data sets were generated to match the actual densities of graphite used in each experiment; and

(5) all calculations were done for a point source, usually 100 cm from the centre of the ion chamber; and source routines were implemented in which the source was not on a symmetry axis because most practical chambers are not symmetric.

The value of A_{wall} is determined by scoring

$$A_{\text{wall}} = A_{\text{sc}} A_{\text{at}} \tag{4}$$

where

$$A_{\text{sc}} = \sum_i (r_i^0 + r_i^1) \left(\sum_i r_i^0 \right)^{-1} \tag{5}$$

$$A_{\text{at}} = \sum_i r_i^0 \left(\sum_i r_i^0 \mathrm{e}^{+d_i} \right)^{-1} . \tag{6}$$

r_i^0 is the energy deposited by electrons generated by the ith primary photon interaction, r_i^1 is the energy deposited by electrons generated from the second and higher-order scattered photons that arise from the ith primary photon and d_i is the number of mean free paths in the chamber to the point of interaction of the ith primary photon. This formulation, which is based on the rigorous treatment in Bielajew (1986), is slightly different from that used in our original paper but the differences have no significant effect on the calculated results.

As a check on the code, for an incident parallel monoenergetic beam of 1.25 MeV photons, we have calculated the dose to the cavity gas per unit incident photon fluence at the centre of a graphite walled ion chamber, divided by A_{wall}. Within the calculation's statistical uncertainty of 0.3%, the ratio agreed with the value predicted by the Spencer–Attix cavity theory (i.e. equation (1) with $A_{\text{oth}} = 1.0$ and other values from Rogers *et al* (1985)). Similar results with 0.4% precision were obtained using the full ^{60}Co spectrum for a point source 100 cm from the cavity (we calculated $K_{\text{col,air}}$ for this spectrum).

2.3. Method for comparison with experiment

The experimental data for $R(t)$ have an accuracy of 0.1% or better. To verify the Monte Carlo calculations, one could do brute force calculations of the chamber response but hundreds of millions of photon histories are needed to achieve a statistical uncertainty of $\pm 0.1\%$. This would take thousands of hours of VAX/780 CPU time per point.

A more precise comparison is obtained by using the fact that achieving the same statistical uncertainty on the calculated values of $A_{\text{wall}}(t)$ instead of $R(t)$ is roughly

100 times faster because the A_{wall} values are based on correlated ratios. To make use of this we write equation (1) as

$$R(t) = R^{CAV} A_{wall}(t) \tag{7}$$

where R^{CAV} is a constant for each cavity, independent of wall thickness once full build-up is achieved. We calculate R^{CAV} as a normalisation factor between the measured values of $R(t)$ and the calculated values of $A_{wall}(t)$ in the full build-up region and take our calculated normalised responses to be $R_{calc}(t_i) = R^{CAV} A_{wall}(t_i)$. To use the same normalisation factor to compare calculations and experiment in the build-up region, we calculate

$$R_{th}^{CAV} = \frac{1}{n} \sum_{i=1}^{n} R(t_i)/A_{wall}(t_i) \tag{8}$$

where $R(t_i)$ and $A_{wall}(t_i)$ are the n Monte Carlo calculated values in the full build-up region, and use $R_{calc}(t_i) = (R^{CAV}/R_{th}^{CAV}) R(t_i)$ as our normalised calculated-values in the build-up region. It should be noted that the calculated values of $R(t_i)/A_{wall}(t_i)$ in the full build-up region are constant within the statistical uncertainty of the $R(t_i)$ calculations, typically 0.5–0.8%. Using this technique means that the relative values of our calculated responses in the full build-up region have a precision equal to that on our calculated values of A_{wall}, i.e. about 0.05–0.1%.

3. Comparison with data from standards laboratories

3.1. The NRCC chamber

The Canadian primary exposure standard for ^{60}Co is based on a cylindrical graphite ion chamber with a large stem. To determine the wall attenuation correction factors, a second chamber (denoted 3AS) was built with a similar cavity but with very thin walls and a series of build-up sleeves and tops. The chamber has an inner radius of 0.792 cm, inner length of 1.806 cm, and an electrode with radius 0.3352 cm and length 1.202 cm inside the cavity. The top wall was 0.097 cm thick for the side wall measurements and the side wall was 0.400 cm thick for the cap measurements. The sleeves for the side wall extended 3.043 cm and the entire region within the sleeves was included in the calculations. The graphite used had a density of 1.66 g cm^{-3}. The source irradiated the chamber from the side at the level of the centre of the air cavity and at a distance of 1 m from the centre of the chamber.

Figure 1 presents a comparison of the experimental and calculated results as the sleeves were added to the side wall. There is agreement at the 0.1% level once full build-up is achieved †. Figure 2 shows the excellent agreement obtained in the full-build-up region as extra thickness was added to the top of the chamber. In the build-up regions of both figures 1 and 2, the measurements either agree with the calculations within the larger statistical uncertainties, or are larger than the calculations. This disagreement is probably caused by electron contamination of the ^{60}Co beam penetrating the chamber walls.

† Since the end cap does not provide full build-up in this case (it is 1% low), the analysis used assumes that the lack of build-up from the end wall remained constant as side wall thickness was increased.

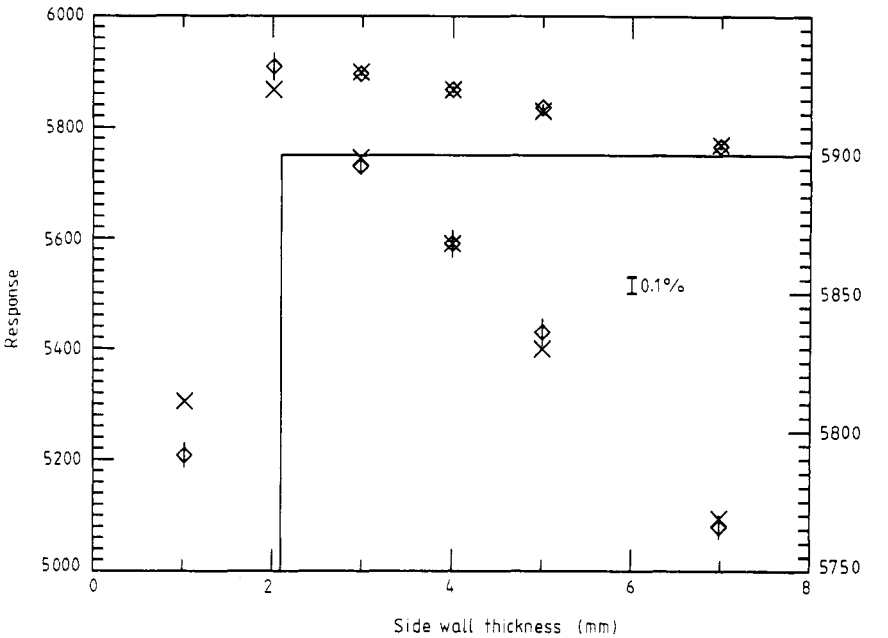

Figure 1. Comparison of calculated (◇) and measured (×) responses of the mock-up (3AS) of the Canadian standard chamber as sleeves are added to the cylindrical wall of the chamber. Experimental data were measured by Henry and reported by Shortt and Ross (1986). Data are normalised as described in section 2.3. Insert is the same data on an expanded scale.

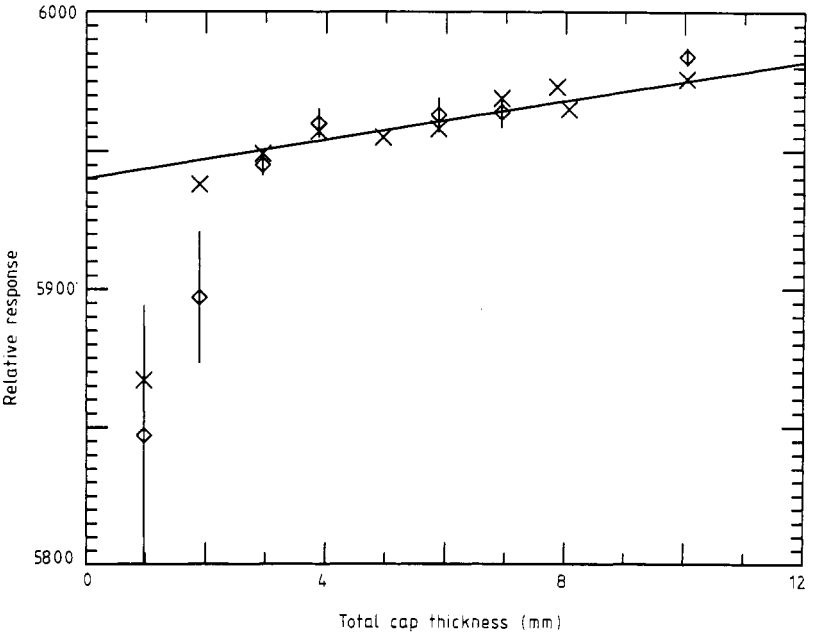

Figure 2. Comparison of calculated (◇) and measured (×) responses of the mock-up (3AS) of the Canadian standard chamber as discs of diameter 23.8 mm are added to the top wall of the chamber. Experimental data were measured by Henry and reported by Shortt and Ross (1986). The line was that used to extrapolate to zero wall thickness to determine A_w for the standard.

3.2. The IRD chamber

Figure 3 presents a similar comparison to the measurements done for the standard chamber of the IRD using the BIPM source (see de Almeida and Niatel 1986; individual data points from de Almeida (1987)). The chamber, which is very similar to that of the ENEA (Italian standards laboratory), is cylindrical with an inner length of 1.1 cm, an inner radius of 0.550 cm, an electrode of radius 0.1 cm and length inside the cavity of 0.85 cm, and with standard walls of 0.400 cm thickness. The chamber has a very thin stem and is irradiated from the side. The graphite has a density of 1.71 g cm^{-3}. The experiment was done by placing complete shells around the entire chamber at the same time. Once again the agreement with experiment is excellent. The experimental data and the value of A_w reported by the ENEA for their chamber are almost identical to that of the IRD (see Laitano and Toni 1983).

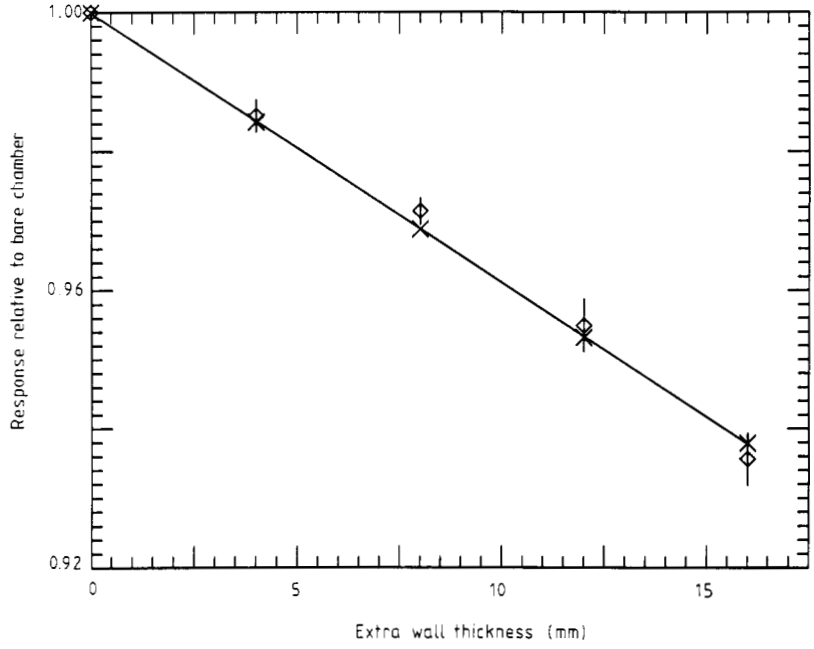

Figure 3. Comparison of calculated (◇) and measured (×) response of the IRD standard chamber as complete shells are added to the chamber. Data are from de Almeida (1987). The base wall was 0.400 cm thick. The line was that used to extrapolate to zero wall thickness to determine A_w for the standard.

3.3. The NIST chambers

Similar calculations were done for several of the NIST (formerly NBS) spherical chambers. Figure 4 shows the results for NIST chamber 50-1 which has a volume of 50 cm^3, walls that are 0.3652 cm thick and is made of graphite with a density of 1.73 g cm^{-3}. The results are in good agreement with the experiment.

3.4. Implications for primary standards

The above comparisons demonstrate that the Monte Carlo calculations agree at the 0.1% level with the experimental data used to determine A_w. Table 1 presents the

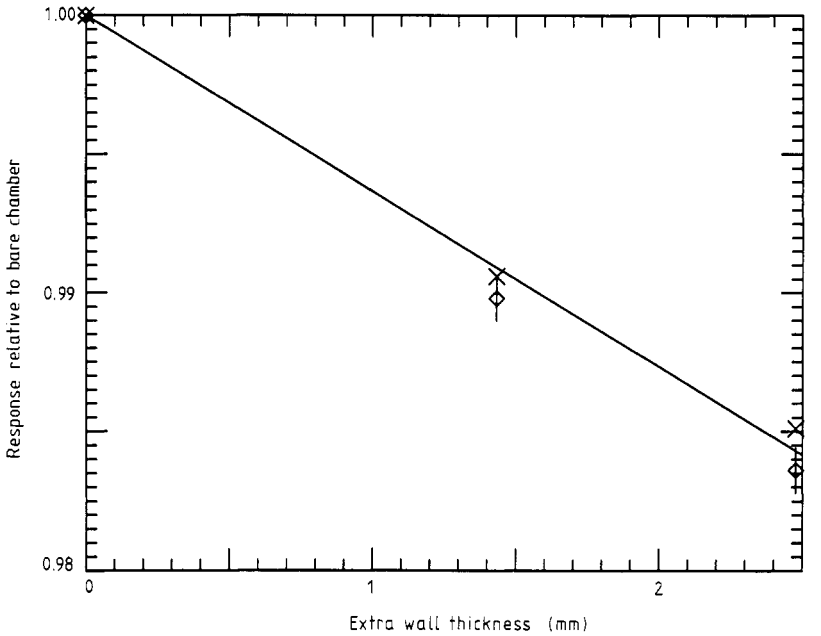

Figure 4. Comparison of calculated (◇) and measured (×) response of the NIST (NBS) standard chamber 50-1. Measured data are from Loftus and Weaver (1974). The line was that used to extrapolate to zero wall thickness to determine A_w for the standard.

Table 1. A_{wall} as used by some standards laboratories and as calculated here along with the 'measured' values of A_w deduced by extrapolating to zero wall thickness. Uncertainties in the last digit (1 σ) are in brackets.

		A_{wall}			
Number	Laboratory/chamber	'Measured'	Calculated	A_w measured	Difference (%)
1	NIST(NBS) 50-1 sphere	0.9827(11)	0.9746(6)	0.9778(5)	−0.82%
2	NIST(NBS) 50-2 sphere	0.9740(11)	0.9646(6)	0.9691(5)	−0.97%
3	NIST(NBS) 50-3 sphere	0.9676(11)	0.9586(7)	0.9627(5)	−0.94%
4	NIST(NBS) 1 sphere	0.9884(18)	0.9790(8)	0.9835(15)	−0.96%
5	NRCC 3C thimble	0.9806(22)[a]	0.9787(3)	0.9757(20)[a]	−0.19%
6	ENEA thimble	0.9875(21)	0.9807(5)	0.9846(5)	−0.69%
7	IRD thimble	0.9876(8)	0.9804(9)	0.9848	−0.73%
8	PTB a thimble	0.9909(16)	0.9915(4)	0.9879(5)	0.06%
9	PTB b thimble	0.9904(18)	0.9888(3)	0.9875(10)	−0.16%
10	PTB c pancake	0.9932(25)	0.9986(7)	0.9903(20)	0.54%
11	BIPM pancake	0.9963(23)	0.9992(6)	0.9887(23)	0.29%

[a] These are the values actually used in the NRCC standard but a more meaningful comparison based on A_w from just the side wall and end wall extrapolations to zero wall thickness would give 'measured' values of A_w = 0.9814 and A_{wall} = 0.9863 which are 0.78% higher than calculated.

Monte Carlo calculated values of A_{wall} for chambers used as standards compared to the values currently used by the individual laboratories, as well as the values of A_w deduced

from the measured wall variation data by linear extrapolation and equation (3).

In view of the quoted uncertainties of about 0.2% or less, the differences found are remarkable, the calculations being as much as 1% lower than the 'measured' data for spherical and near-spherical chambers, and up to 0.5% higher than 'measured' for pancake chambers. The calculations are within 0.2% of the measured values for the thimble ionisation chambers. Figure 5 summarises the differences between the measured and calculated values of A_{wall}. There is a clear relationship between the chamber geometry and the size of the difference.

An even more startling result is that the measured A_w values are often greater than the calculated A_{wall} values. If the measured A_w values were smaller than the calculated A_{wall} values, it would be possible that errors in calculating A_{cep} were the cause of the discrepancies between measured and calculated A_{wall} values. However, having A_w values greater than the calculated A_{wall} values implies that the problem cannot be associated only with the calculation of A_{cep} since by definition A_{cep} is greater than unity.

To explain these results, the linear extrapolation of wall attenuation data has been investigated and found to be incorrect for spherical chambers (Bielajew 1990a). In conjunction with the results found here, this casts significant doubt on the linearity of the extrapolation in other cases.

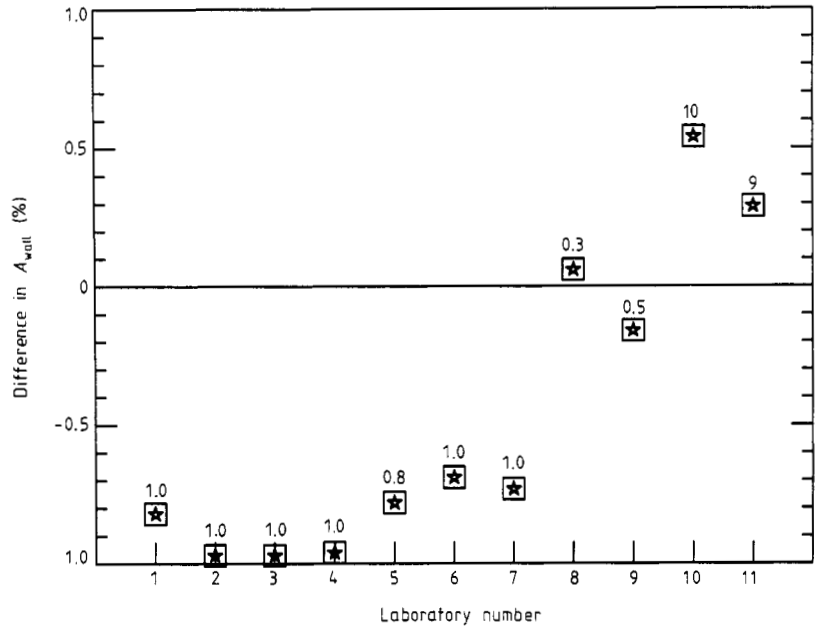

Figure 5. A summary of the percentage difference (calculated less measured) between the calculated and measured A_{wall} values for various ^{60}Co primary standards. The figures above each symbol are the ratio of the cavity's diameter to its height. For laboratory numbers, see table 1.

Since (i) the Monte Carlo calculations are capable of reproducing all the experimental data available, (ii) the electron transport included in the Monte Carlo calculations is at least as sophisticated as that used in any of the previous estimates of A_{cep}, and (iii) there is no rigorous justification available for the linear extrapolation technique, we thus believe that the calculated values are the most accurate estimates of the A_{wall} correction factors.

4. A_{wall} for clinical chambers

Many current clinical dosimetry protocols make use of calculated A_{wall} values for clinical chambers (e.g. AAPM 1983, IAEA 1987). In view of the discrepancies discussed in section 3 concerning values based on extrapolation techniques, the use of these calculated values seems appropriate.

Nonetheless, the currently used values, which are based on the results of Nath and Schulz (1981) and/or Rogers *et al* (1985), are based on several approximations, notably use of a symmetric build-up cap which has a uniform thickness on the sides and *both* end walls of the chamber, as well as use of a monoenergetic 1.25 MeV photon source.

Rocha *et al* (1989) at the IRD have recently done a series of very precise measurements using clinic-like build-up caps of different materials and wall thicknesses, all placed on the same high precision Delrin-walled thimble ion chamber. These build-up caps are far from symmetric about the gas cavity. In all cases a 2 mm thick throat extended down the stem 15 mm below the gas cavity and the extra build-up extended 5 mm below the gas cavity. The experimental data were compared to those of Nath and Schulz by comparing the measured slope of the $R(t)$ against wall thickness curves to the value of $-\gamma$ (Nath and Schulz 1981, AAPM 1983) which gives the wall attenuation correction per unit wall thickness. The predicted value for the IRD chamber with an inner diameter of 7 mm and axial length of 12 mm is -0.021 cm^2 g^{-1}. The experimental values of Rocha *et al* (1989) for build-up caps of Delrin, graphite, PMMA, C-552 and A-150 were all within ± 0.001 of -0.029 cm^2 g^{-1}. It is tempting to use this experimental value in the formula of Nath and Schulz for determining A_{wall} (namely $A_{wall}(t) = 1 - t\gamma$), in which case the values of A_{wall} deduced are lower than those of Nath and Schulz by 0.4–0.5% for wall thicknesses of about 0.5 g cm^{-2}. However this approach is conceptually incorrect since using the measured value of γ in this way is equivalent to extrapolating to zero wall thickness, which determines A_w, not A_{wall} †. Using a typical value of $A_{cep} = 1.005$ implies that A_{wall} values deduced from the A_w values of Rocha *et al* are in good agreement with the A_{wall} values of Nath and Schulz.

However, the logic of the above procedure is still incorrect since, as discussed in section 3, the linear extrapolation technique does not work in general. Also, the experimental values of γ clearly disagree with the calculated values. When modelling the geometry of the build-up cap geometries more exactly we calculate $\gamma = 0.027 \pm 0.002$ cm^2 g^{-1} for the Delrin, graphite and PMMA build-up caps. As shown in figure 6, this is in more satisfactory agreement with the experimental data than are the calculations of Nath and Schulz. On redoing our calculations for symmetric walls and a 1.25 MeV photon source, we calculate $\gamma = 0.025 \pm 0.002$ cm^2 g^{-1} which is still in reasonable agreement with the experimental data (figure 6). This indicates that the differences are not from more accurately modelling the build-up cap, but from differences between our Monte Carlo calculations and those of Nath and Schulz which are also known to calculate the chamber's response improperly (Rogers *et al* 1985).

However, the effect of the differences in the Monte Carlo codes on the calculated values of A_{wall} are very small. For the 0.5 g cm^{-2} thick walls our calculations show an increase of about 0.15% and a corresponding small decrease for the 0.9 g cm^{-2} thick build-up caps. These small changes imply a significant improvement in the agreement

† The fact that the values of Nath and Schulz can be parametrised well as $A_{wall} = 1 - t\gamma$ is fortuitous and should not be used to extrapolate to zero wall thickness.

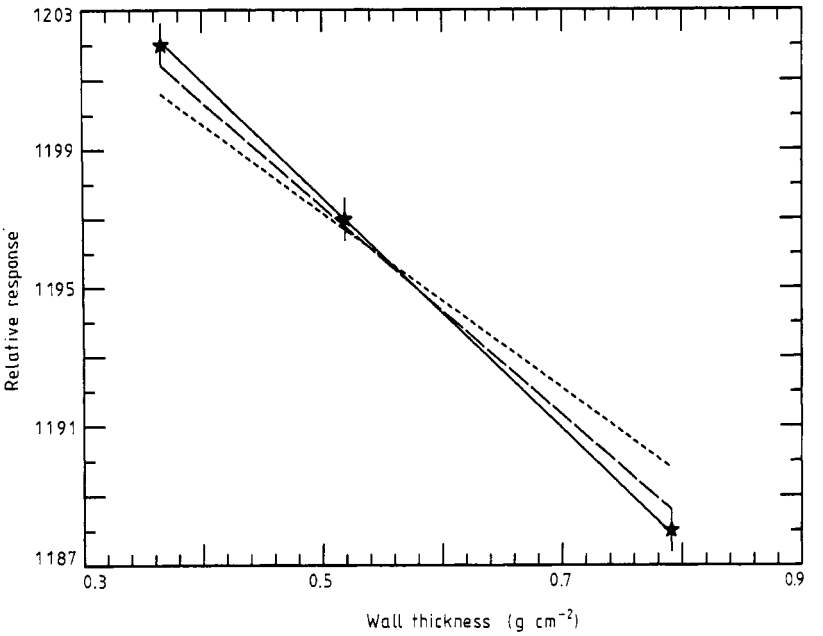

Figure 6. Comparison of measured and calculated responses of a commercial thimble chamber as the build-up cap walls of Delrin were made thicker. Full stars, measured data (Rocha *et al* (1989)); short dash line, predictions of the Nath and Schulz calculations of A_{wall}; full line, EGS4 values for a complete ^{60}Co spectrum and a realistic model of the build-up caps; long-dash line, model with symmetric walls and build-up cap and monoenergetic 1.25 MeV photons.

with the experimental data of Rocha *et al*, and are consistent with the size of the differences we found in a previous comparison of A_{wall} values for a large number of specific commercial ion chambers (Rogers *et al* 1985).

The results of Rocha *et al* confirm the assumption that the value of A_{wall} does not depend on the material of the build-up cap for five commonly used low-density materials. They also presented data for aluminium build-up caps, which showed $\gamma = 0.024$ cm^2 g^{-1}. This is different from the other values but in good agreement with our calculated value of 0.025 ± 0.002 cm^2 g^{-1} for an aluminum build-up cap. However, our calculated value of A_{wall} for a 0.5 g cm^{-2} walled aluminum build-up cap is within 0.04% of the universal value predicted from the Nath and Schulz values of γ.

Another point with respect to A_{wall} factors for clinical chambers is that the experimentally determined values of A_{wall} (K_{att}) used in the NACP protocol (1980) for thimble chambers are in good agreement with the Monte Carlo calculated values for those chambers. This is consistent with the result for a similar thimble chamber shown as laboratory 8 in figure 5 and table 1 and with the observation above that extrapolating the data of Rocha *et al* to zero wall thickness and multiplying by A_{cep} gives the same value for A_{wall} as the Monte Carlo calculations.

5. Conclusions

In regions of full build-up, the Monte Carlo calculations of A_{wall}, and hence relative response against wall thickness have been shown to be in good agreement, to better than 0.1%, with all the high-quality experimental data which we have access to.

These comparisons are relative. It cannot be completely ruled out that the calculations contain some constant offset. However, the calculated response divided by A_{wall} has been shown to agree with the theoretical Spencer–Attix cavity theory value to within a statistical precision of 0.3%, which suggests an absolute accuracy in the calculations which is at least this good. In view of the fact that the calculations agree with the experimental data but imply substantially different A_{wall} values from those derived using extrapolation techniques, and in view of the problems isolated elsewhere concerning the extrapolation theory (Bielajew 1990a), we believe that the calculated values of A_{wall} are the most accurate available and they are being adopted for use in the Canadian primary standard.

Using calculated correction factors would imply increases of 0.7–1.0% in the exposure and air kerma standards based on spherical and large diameter, large length cylindrical chambers and decreases of 0.3–0.5% for standards based on large diameter pancake chambers. This is a startling result because many of these standards have been intercompared and found to be consistent with a scatter of $\pm 0.2\%$. However, in another paper (Bielajew 1990c) there are changes proposed in the correction factors related to the point source nature of the radiation field used in exposure and air kerma standards. These proposed changes offset the changes implied by the A_{wall} changes proposed here in such a way that the consistency among the standards is maintained.

Use of the calculated values would also lead to a consistent dosimetry chain because calculated A_{wall} values are used in clinical dosimetry protocols.

The comparisons with experimental data for a clinical chamber and build-up caps indicate good agreement with the present Monte Carlo calculations although there is a small but distinct discrepancy with the predictions of Nath and Schulz (1981). This appears to be due to differences in the Monte Carlo codes rather than the more complete modelling of the geometry used here. Nonetheless, the Nath and Schulz values of A_{wall} agree within 0.2% with the more accurate calculations.

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Résumé

Corrections pour la diffusion et l'atténuation de la paroi pour les chambres d'ionisation: mesures et calculs.

En dosimétrie de précision dans l'air réalisée à l'aide de chambres d'ionisation, la diffusion et l'atténuation de la paroi sont corrigées par A_{wall} (K_{att} dans le formalisme AIEA, K_w^{-1} dans la terminologie des laboratoires de référence). Utilisant le programme EGS4, les auteurs montrent que les facteurs A_{wall} calculés par la méthode de Monte Carlo prédisent des variations relatives de la réponse du détecteur en fonction de l'épaisseur de la paroi qui sont en accord avec toutes les données expérimentales disponibles avec une incertitude statistique inférieure à 0,1%. Cependant, ils obtiennent par le calcul des facteurs de correction à utiliser pour les références d'exposition et de kerma dans l'air qui sont différents jusqu'à 1% de ceux obtenus par extrapolation de ces mêmes mesures. L'utilisation des facteurs de correction calculés conduirait à augmenter de 0,7% à 1% les références d'exposition et de kerma dans l'air obtenues par les chambres cylindriques de grande longueur et

de grand diamètre et à diminuer de 0,3 à 0,5% ces références obtenues avec des chambres plates de grand diamétre. Les auteurs montrent également que les calculs sont en accord à mieux que 0,05% avec les mesures de Rocha et de son équipe pour les chambres utilisées en clinique. Ces données expérimentales ne sont sont pas en accord parfait avec les valeurs utilisées dans le protocole AAPM pour l'obtention de A_{wall}. Cependant, les valeurs finales AAPM de A_{wall} sont en accord à mieux que 0,2% avec les valeurs de γ les plus précises calculées dans cet article.

Zusammenfassung

Wand-Schwächungs- und Streukorrekturen für Ionisationskammern: Messungen im Gegensatz zu Berechnungen.

Bei der Präzisionsdosimetrie in Luft mit Hilfe von Ionisationskammern wird die Schwächung und die Streuung durch die Kammerwände korrigiert durch A_{wall} (k_{att} in IAEA Terminologie, K^{-1} in Standardlabor Terminologie). Unter Verwendung des EGS4 Programms wird gezeigt, daß die mit Hilfe der Monte Carlo Methode berechneten A_{wall}-Faktoren relative Schwankungen des Detektorverhaltens mit der Wanddicke vorhersagen, die mit allen verfügbaren experimentellen Daten innerhalb eines statistischen Fehlers von unter 0.1% übereinstimmen. Die berechneten Korrekturfaktoren bei der Ionendosis und der Luftkerma sind jedoch bis zu 1% verschieden von den Faktoren, die man durch Extrapolation dieser Messungen erhält. Die verwendung berechneter Korrekturfaktoren hätte eine Erhöhung der Ionendosis und der Luftkermastandards auf der Grundlage kugelförmiger Kammern mit großem Durchmesser und zlindrischer Kammern großer Länge um 0.7 bis 1% zur Folge und eine Verringerung von 0.3 bis 0.5% bei Standards auf der Grundlage von Flachkammern mit großem Durchmesser. Außerdem wird gezeigt, daß die Berechnungen innerhalb von 0.05% mit den Messungen von Rocha und seinen Mitarbeiten für klinische Kammern übereinstimmen. Diese experimentellen Daten befinden sich nicht in sehr genauer Übereinstimmung mit den γ-Werten, die im AAPM Protokoll verwendet werden um A_{wall} zu erhalten. Die endgüligen AAPM werte für A_{wall} stimmen jedoch innerhalb von 0.2% mit den hier berechneten, viel genaueren Werten überein.

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