On the accuracy of techniques for obtaining the calibration coefficient N_K of ^{192}Ir HDR brachytherapy sources

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The accuracy of interpolation or averaging procedures for obtaining the calibration coefficient N_K for ^{192}Ir high-dose-rate brachytherapy sources has been investigated using the EGSnrc Monte Carlo simulation system. It is shown that the widely used two-point averaging procedure of Goetsch *et al.* [Med. Phys. **18**, 462 (1991)] has some conceptual problems. Most importantly, they recommended, as did the IAEA, averaging $A_{\text{wall}}N_K$ values whereas one should average $1/N_K$ values. In practice this and other issues are shown to have little effect except for Goetsch *et al.*'s methods for determining A_{wall} values. Their method of generalizing the A_{wall} values measured in one geometry to other geometries is incorrect by up to 2%. However, these errors in A_{wall} values cause systematic errors of only 0.3% in ^{192}Ir calibration coefficients. It is shown that A_{wall} values need not be included in the averaging technique at all, thereby simplifying the technique considerably. It is demonstrated that as long as ion chambers with a flat response are used and/or very heavily filtered 250 kV (or higher) beams of x rays are used in the averaging, then almost all techniques can provide adequate accuracy.
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Key words: ^{192}Ir, HDR, brachytherapy, calibration procedures

I. INTRODUCTION

The steady increase in the use of ^{192}Ir high-dose-rate (HDR) sources for brachytherapy in the early 1990s made necessary the development of a manufacturer independent calibration procedure for these sources. Since NIST did not offer calibrations of ionization chambers for ^{192}Ir HDR sources, in 1991 Goetsch *et al.*[1] proposed a technique to estimate N_K, the air-kerma calibration coefficient for an ^{192}Ir HDR brachytherapy source, by averaging calibration coefficients. This technique has since been recommended by the IAEA for use by Secondary Standard Dosimetry Laboratories (SSDLs).[2] In the meantime, Borg *et al.*[3] showed that one could apply Spencer-Attix cavity theory successfully in an ^{192}Ir beam as long as the ion chamber had graphite walls. BARC (India's primary standards laboratory) has produced a cavity ion chamber-based primary standard for ^{192}Ir HDR sources[4,5] and NPL (Britain's primary standards laboratory) offers a service based on such a standard. However, much of the rest of the world still use various interpolation techniques.

Goetsch *et al.*[1] suggested that available air-kerma calibration coefficients from primary standards laboratories for 250 kV medium filtered x-ray and ^{137}Cs beams could be averaged to estimate the air-kerma calibration coefficient, N_K, of the ^{192}Ir brachytherapy source. This is based on the fact that the average energy of the ^{192}Ir spectrum (397 keV for a bare source, 357 keV from an HDR source) lies roughly halfway between the average energy of the 250-kV x-ray beam they were using (146 keV) and the 613-keV average energy of a 662-keV ^{137}Cs gamma-ray source. An assumption underlying this technique is that the ionization chambers used have a well behaved calibration curve as a function of energy. This calibration procedure is currently used at the University of Wisconsin Accredited Dosimetry Calibration Laboratory (UWADCL).[1,6] This technique is, in principle, on shaky ground, since, as shown below, to get a rigorous value of N_K for a spectrum one needs to evaluate a weighted average of ion chamber response, which is proportional to $1/N_K$, not the ion chamber calibration coefficient, N_K.[7–11] A primary goal of this study is to investigate how serious an error is made when averaging N_K values. When there is little variation in the calibration coefficients versus beam energy, the differences in the two techniques are not large. Another goal is to investigate the concept of including corrections for wall attenuation and scatter in the method of Goetsch *et al.*[1] as well as the actual values of the corrections they recommended.

A logically rigorous method for calibrating brachytherapy sources with a complex energy spectrum is to use an air-kerma weighted average of inverse calibration coefficients N_K for the individual spectral lines.[7,8,11,12] This procedure requires a calibration curve for the chamber in the energy range of interest and a calculation of the relative air-kerma strength of each photon line in the ^{192}Ir spectrum based on a knowledge of the energy fluence spectrum of the ^{192}Ir source at the cavity chamber. This spectrum cannot be calculated simply by attenuating the initial spectrum lines as done by some,[8,11] since scattered photons contribute about 6.6% to the photon fluence of a spectrum from a realistic source.[13] Interactions in the air lead to only a slight decrease in the photon's energy in the vast majority of the cases and virtually no decrease in the overall fluence. Another difficulty arising when applying this method is that the standard x-ray beams most commonly used to obtain the chamber calibration curve have heavy filtration with low air-kerma rates.[9] This method is widely used.[7–12] However, even this technique requires an assumption about the shape of the ion chamber's response curve between the x-ray beam of the highest mean energy (typically about 200 keV) and a ^{137}Cs beam, since the vast majority of the ^{192}Ir air-kerma strength comes from photons in this energy region. In practice a linear interpolation is often made of the calibration coefficient or the energy response between two beam qualities (^{137}Cs or ^{60}Co and an x-ray beam).[11] This assumption about the shape can, in principle, lead to significant errors but should not be critical in practice since chambers used for calibrations can be selected to have flat responses versus energy in this region. A further aim of this study is to investigate the accuracy of the standard approximation that the response or calibration coefficient versus beam quality is linear in this region.

Due to the absence of generally available primary air-kerma standards for ^{192}Ir HDR brachytherapy sources, and the complexity of the ^{192}Ir spectrum, the accuracy of current interpolation procedures for the calibration of these sources is difficult to establish experimentally. For this reason, we have resorted to the Monte Carlo method, which has been shown to estimate accurately both the dose inside the cavity of an ion chamber and A_{wall}, the correction factor for attenuation and scatter in the chamber's wall.[3,14–21] In particular, Seuntjens *et al.*[17] demonstrated that EGSnrc calculates ion chamber response with an accuracy of 0.1% relative to its own cross sections down to a mean photon energy of about 100 keV which makes it an ideal tool for this work.

II. METHODS

A. The air-kerma calibration coefficient, N_K

The air-kerma calibration coefficient, N_K, relates a corrected ion chamber charge reading, M, to the air kerma, K_{air}, at the center of the chamber when it is absent, i.e.,

$$N_K = \frac{K_{\text{air}}}{M}. \tag{1}$$

From the definitions of the quantities involved, the quantity M is related to D_{gas}, the dose to the gas in the chamber, by

$$D_{\text{gas}} = M\left(\frac{W}{e}\right)_{\text{gas}} \bigg/ m_{\text{gas}}, \tag{2}$$

where $(W/e)_{\text{gas}}$ is the mean energy lost in the gas per Coulomb of charge released and m_{gas} is the mass of the gas in the ion chamber. Using this with Eq. (1) gives

$$N_K = \left(\frac{W}{e}\right)_{\text{gas}} \frac{1}{m_{\text{gas}}} \frac{K_{\text{air}}}{D_{\text{gas}}} = \left(\frac{W}{e}\right)_{\text{gas}} \frac{1}{m_{\text{gas}}} N'_K, \tag{3}$$

where the dimensionless quantity $N'_K(\equiv K_{\text{air}}/D_{\text{gas}})$ is directly proportional to N_K and is introduced for presenting the various calculated results since it is close to unity.

Using the equation for air kerma that is used to establish a primary standard by using a cavity ion chamber (see, e.g., Ref. 18), one finds

$$N_K = \frac{\left(\frac{W}{e}\right)_{\text{air}}}{m_{\text{air}}(1-\bar{g}_{\text{air}})} \left(\frac{\bar{L}}{\rho}\right)^{\text{wall}}_{\text{air}} \left(\frac{\overline{\mu_{\text{en}}}}{\rho}\right)^{\text{air}}_{\text{wall}} \times K_h K_{\text{wall}} K_{an} K_{\text{comp}} K \ (\text{Gy}/C), \tag{4}$$

where m_{air} and $(W/e)_{\text{air}}$ are now with respect to dry air in the chamber, $\bar{g}_{\text{air}}$ is the fraction of the energy of an electron lost in radiative events while slowing in air, $(\bar{L}/\rho)^{\text{wall}}_{\text{air}}$ is the Spencer-Attix mass collision stopping-power ratio for the wall material to dry air, $(\overline{\mu_{\text{en}}}/\rho)^{\text{air}}_{\text{wall}}$ is the ratio of mass energy absorption coefficients averaged over the spectrum for dry air to the wall material, K_h is the humidity correction factor[22] which changes the references to gas (i.e., the humid air) to dry air, K_{wall} corrects for the attenuation and scatter in the chamber wall ($K_{\text{wall}}=1/A_{\text{wall}}$), K_{an} corrects for the axial nonuniformity due to the point source nature of the beam instead of the photon beam being parallel, K_{comp} is a correction for the composite, i.e., nonuniform, nature of the wall material (e.g., for a cap, if it is of different material), and K includes various corrections for other nonideal conditions (e.g., corrections for stems, central electrodes of different material from the wall, radial nonuniformity of the beam, etc.). Note that this equation only applies in photon beam qualities for which Spencer-Attix cavity theory applies.[3] It does not apply for lower-energy x-ray beams as was assumed in a recent paper,[11] which also ignored the need for the central electrode correction factor. This latter correction factor is a 0.8% effect at ^{60}Co beam qualities for ion chambers with an aluminum electrode,[23,24] and is presumably much greater at lower energies since the whole purpose of the aluminum electrode is to flatten the response of graphite-walled ion chambers.

B. Averaging N_K at two beam qualities

As mentioned above, Goetsch *et al.*[1] developed a calibration procedure for ^{192}Ir HDR brachytherapy sources based on the simple averaging of available NIST traceable air-kerma calibration coefficients, N_K, for a 250-kV medium filtered x-ray beam and a ^{137}Cs beam.

Goetsch *et al.* declared that "attenuation must be explicitly accounted for" because the calibration coefficients are being interpolated. We will discuss this in more detail below, but referring to Eq. (4) for N_K, accounting for attenuation amounts to taking into account the variation in the K_{wall} correction factor while inexplicably ignoring the changes in all other factors on the right-hand side of the equation. To explicitly account for attenuation in the chamber walls, Goetsch *et al.* averaged the product $N_K A_{\rm wall}$ instead of averaging the calibration coefficients directly, i.e.,

$$(A_{\rm wall}N_K)_{^{192}\rm Ir} = \tfrac{1}{2}[(A_{\rm wall}N_K)_{250\ \rm kV} + (A_{\rm wall}N_K)_{^{137}\rm Cs}]. \tag{5}$$

The measurements reported in their paper were made with a Farmer ionization chamber to determine the wall correction factors, $A_{\rm wall}$, in beams of ^{192}Ir, ^{137}Cs, and 250 kV medium filtered x-rays, by extrapolating measured values of response with increased wall thicknesses.[14]

Making use of their numerical values for $A_{\rm wall}$ in Eq. (5), they derived an approximate expression for $(N_K)_{^{192}\rm Ir}$, i.e.,

$$(N_K)_{^{192}\rm Ir} = \tfrac{1}{2}(1+x)[(N_K)_{250\ \rm kV} + (N_K)_{^{137}\rm Cs}]. \tag{6}$$

where $x=0.0037\ [t/(9.3\times 10^{-22})]$ for a wall thickness of t electrons/cm^2. For instance, x equals 0.0037 for a chamber with a graphite wall thickness of 0.31 g/cm^2 and 0.0053 for an Exradin A3 spherical chamber with a wall+cap thickness of 0.44 g/cm^2. As an example, Goetsch *et al.* applied this method when using an Exradin A3 spherical chamber of volume 3.6 cm^3 for which NIST-traceable calibration coefficients were available.

Equation (6) was recommended by Goetsch *et al.* and by the IAEA (Ref. 2) as a general expression to be used for any reference ionization chamber when averaging with a ^{137}Cs beam. In addition to the conceptual error mentioned above about averaging of $A_{\rm wall}N_K$ values rather than $1/N_K$ values and the uncertainty about giving $A_{\rm wall}$ a special status, this equation is, in principle, incorrect because the $A_{\rm wall}$ values will differ for differently shaped ion chambers of the same wall thickness. For example, for a fixed wall thickness, Table III of the TG-21 protocol shows over a factor of 2 variation in the difference between $A_{\rm wall}$ values and unity.

C. Averaging response weighted by air kerma

To derive an accurate expression for the calibration coefficient, N_K, for any photon spectrum with many energies, one considers $D_{\rm air}(E_i)$, the response or dose to the air in the ion chamber due to the fluence of photons of a given energy E_i. Physically, it is clear that the dose due to any spectrum of lines, e.g., ^{192}Ir, is made up of a sum of the doses from the individual lines, i.e.,

$$D_{\rm gas}(^{192}\rm Ir) = \sum_i D_{\rm gas}(E_i), \tag{7}$$

Rearranging Eq. (3) for N_K in terms of $K_{\rm air}/D_{\rm gas}$, and substituting into the equation above,

$$\frac{K_{\rm air}(^{192}\rm Ir)}{N_K(^{192}\rm Ir)} = \sum_i \frac{K_{\rm air}(E_i)}{N_K(E_i)}, \tag{8}$$

where $K_{\rm air}(E_i)$ is the component of the air kerma due to photons of energy E_i, and $N_K(E_i)$ is the chamber's air-kerma calibration coefficient for photons of energy E_i. This implies

$$\frac{1}{N_K(^{192}\rm Ir)} = \sum_i \frac{K_{\rm air}(E_i)}{K_{\rm air}(^{192}\rm Ir)}\left(\frac{1}{N_K(E_i)}\right), \tag{9}$$

i.e., the calibration coefficient can be rigorously calculated as the air-kerma weighted average of the chamber response (N_K^{-1}) for the individual spectral lines. Note that $A_{\rm wall}$ does not occur in this rigorously derived equation. Equation (9) is not new and is the basis of the technique used by many laboratories.[7–12] Although this equation is exact, to apply it one requires the response of the chamber as a function of the photon energy in the energy range of interest and in practice this still requires assumptions about the shape of the response curve as a function of beam quality. Applying this equation also requires the photon energy fluence spectrum of the ^{192}Ir source at the position of the chamber. Borg *et al.* have calculated these spectra for a variety of different ^{192}Ir source types.[13,25]

If one makes the assumption that the ^{192}Ir spectrum can be approximated by an x-ray beam and a ^{137}Cs beam of equal air-kerma rates, then Eq. (9) implies

$$\frac{1}{N_K(^{192}\rm Ir)} = \left(\frac{1}{N_K(\rm x\ ray)} + \frac{1}{N_K(^{137}\rm Cs)}\right) \Big/ 2. \tag{10}$$

This approximation is not strictly valid but this approach strongly suggests that Eq. (10) is the appropriate way to do a simple averaging of calibration coefficients. However, if the variation in N_K values is small, averaging N_K or $1/N_K$ yields virtually identical results. Nonetheless, Eq. (10) is the appropriate equation to use. Furthermore, this equation demonstrates clearly that no $A_{\rm wall}$ value is required in the averaging.

D. Monte Carlo calculations

The first stage of this project was to investigate the energy dependence of different quantities affecting the calibration coefficient for a 0.6-cm^3 thimble ionization chamber with 0.51 g/cm^2-thick graphite walls. Applying Spencer-Attix cavity theory, the qualitative influence on the calibration coefficient of the various beam-quality-dependent quantities in Eq. (4) for N_K can be investigated, even though Borg *et al.*[3] showed that Spencer-Attix cavity theory breaks down by more than 1.5% at 100 keV.

Stopping-power ratios of medium to air were calculated with the NRC user code SPRRZnrc,[26] which makes use of restricted stopping powers based on ICRU Report 37.[27] The kerma per unit energy fluence in a given medium, i.e., the mass-energy transfer coefficient, was calculated using the EGSnrc user code DOSRZnrc[26] forcing photons to interact in a very thin slab of material and scoring all the energy transferred on the spot. To get the mass-energy absorption coefficient, the fraction of the electron's energy lost via radiative processes, $\bar{g}$, was calculated using the EGSnrc user code "g",[3] which scores $\bar{g}$ as the ratio of the energy radiated by electrons slowing down in an infinite medium to the total energy transferred by photons to electrons. The dose to the gas cavity of the ionization chamber, $D_{\rm gas}$, was calculated with the EGSnrc user-code CAVRZnrc.[26]

To assess the accuracy of the two techniques described above for obtaining N_K, we have used the EGSnrc Monte Carlo simulation system and the user-codes CAVRZnrc and CAVSPHnrc (Ref. 28). We have modeled several different chambers. The first is a generic 0.6-cm^3 thimble chamber with 0.31 g/cm^2-thick graphite walls and a graphite electrode to correspond to the unspecified graphite-walled chamber used by Goetsch *et al.*[1] A similar chamber with 0.51 g/cm^2-thick walls was also modeled. To model a realistic NE2571 Farmer chamber (Nuclear Enterprises, Ltd., Fairfield, NJ), we used information extracted from the manufacturer's instruction manual and the paper by Aird and Farmer.[29] The NE2571's graphite wall was taken as 0.065 g/cm^2 thick with a density of 1.73 g/cm^3. The buildup cap used in the calculations was either 0.39 g/cm^2-thick graphite or the more standard 0.55 g/cm^2-thick Delrin® (DuPont) walls. In addition, an Exradin A3 spherical ion chamber (Standard Imaging, Inc., Middleton, WI) was modeled in accordance with the manufacturer's specification sheet as a spherical shell with 0.449 g/cm^2-thick walls of C552 (Shonka air-equivalent conductive plastic) with density 1.76 g/cm^3. For the A3 no C552 electrode was modeled since there is no possibility of modeling mixed spherical and cylindrical geometries in the EGSnrc user-codes being used. However, the effect of the electrode on the dose to the gas cavity and the wall correction factor A_{wall} was found to be negligible by including a sphere made of C552 inside the cavity with the same mass as the actual electrode.

One can compare the calculated to the measured ratio of calibration coefficients for the ^{137}Cs and 146 keV x-ray beams. The latter beam is used since this is the mean energy of the 250-kV beam used by Goetsch *et al.*, and we do not know the spectrum although, as will be shown below, the calculated responses for chambers in x-ray spectra are very similar to the calculated response for monoenergetic photons with the mean energy of the spectrum. The measured ratio is 1.0079 compared with the calculated ratio of 1.0024. This is considered to be in reasonable agreement considering the uncertainties of about 0.5% in the respective measured values which are based on two unrelated standards (a free-air chamber and a cavity ion chamber), both of which have undergone significant changes in the past few years. Given the demonstrated accuracy of the Monte Carlo code,[15,17] it is likely that the calculated ratio is more accurate than the measured ratio since the two calculations are correlated and many uncertainties drop out.

The Monte Carlo calculations gave the dose deposited in the cavity of the above-mentioned chambers by: monoenergetic photons (100 keV–1.1 MeV); 250 kV x-ray beams from the spectra compilation by Seelentag *et al.*,[30] with light (E_{ave}=111.6 keV, 5 mm Al+1 mm Cu), medium (E_{ave}=137.5 keV, 5 mm Al+3.2 mm Cu), and heavy (E_{ave}=205.6 keV, 4 mm Al+2 mm Sn+3 mm Pb) filtration; ^{137}Cs photons (spectrum from the EGSnrc distribution, E_{ave}=613 keV); an ^{192}Ir HDR MicroSelectron brachytherapy source (spectrum from Borg and Rogers,[13,25] E_{ave}=357 keV); and a ^{60}Co beam (spectrum from Rogers *et al.*,[31] E_{ave}=1047 keV). The air-kerma per unit energy fluence and the fraction of the electron's energy lost via radiative processes were calculated as described above.

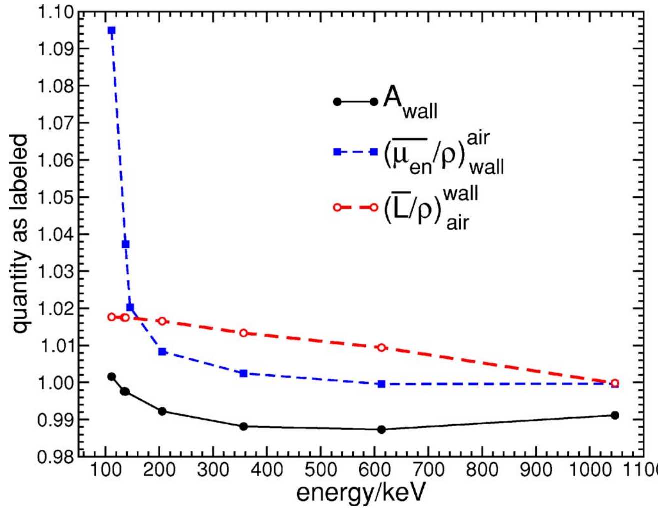

FIG. 1. Energy dependence of different quantities affecting the calibration coefficient N_K for a 0.6-cm^3 graphite-walled thimble chamber of thickness 0.5 g/cm^2. The mass energy absorption coefficient ratios $(\overline{\mu_{en}}/\rho)^{\mathrm{air}}_{\mathrm{wall}}$ show the strongest energy dependence. Calculations are for three 250-kV x-ray beams (light filtration, E_{ave}=112 keV; medium filtration E_{ave}=138 keV; heavy filtration, E_{ave}=206 keV), a monoenergetic 146-keV beam, an ^{192}Ir beam from an ^{192}Ir HDR MicroSelectron source (Ref. 13), a ^{137}Cs beam, and a ^{60}Co beam.

III. RESULTS

A. Inclusion of A_{wall}

Figure 1 shows, as a function of average spectrum energy, the calculated variation of the various factors which affect N_K values in Eq. (4). The point is that A_{wall}, the attenuation and scatter correction, holds no special status.

Figure 2 shows calculated N'_K values for a variety of spectra as a function of their average photon energies for the 0.6-cm^3 graphite-walled thimble chamber with 0.31 g/cm^2-thick walls and graphite electrode. The different curves present the effect on N'_K of removing the influence of different quantities and, as we will show below, the flatter the resulting curve is, the more accurate is any interpolation or averaging technique. Removing the influence of K_{wall} (A^{-1}_{wall}) on N'_K still leaves a strong energy dependence. The energy dependence of the calibration coefficient, N_K, is mainly governed by the energy dependence of the mass-energy absorption coefficient ratios $(\overline{\mu_{en}}/\rho)^{\mathrm{air}}_{\mathrm{wall}}$, but only after removing the influence of all factors is an almost energy-independent value obtained. There is no *a priori* motivation for only removing the A_{wall} dependence.

How big an effect does the inclusion of the A_{wall} factors have on an ^{192}Ir calibration coefficient based on Eqs. (5) or (6)? If one does a simple averaging of the UWADCL's calibration coefficients for their Exradin A3 chamber instead of using their equation with their A_{wall} values, the implied ^{192}Ir calibration decreases by 0.53%.

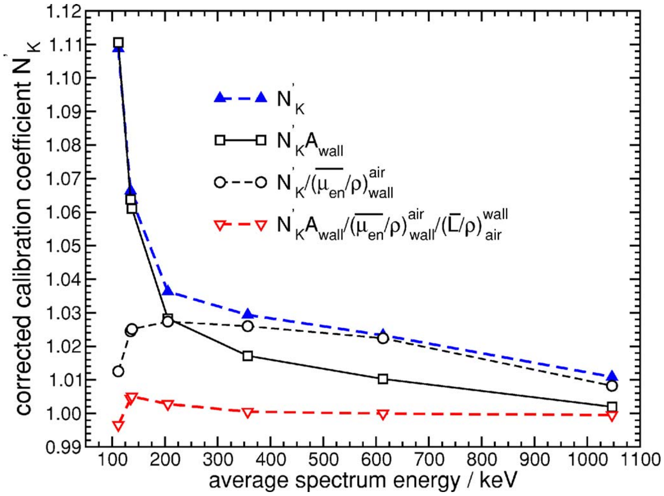

FIG. 2. Calculated N_K' and related values vs average spectrum energy for a 0.6-cm^3 graphite-walled thimble ionization chamber with a wall thickness of 0.5 g/cm^2. The same spectra as in Fig. 1 are used. The different curves represent the effect of taking out the influence of different quantities on N_K'. By removing the influence of A_{wall}^{-1} on N_K', a strong energy dependence is still observed. An almost energy-independent value is obtained only after removing the influence of all other factors.

B. Accuracy of A_{wall}

As well as the issue of whether A_{wall} should be included in the equation for the ^{192}Ir calibration coefficient, there are important questions about the values in use. There has been concern about the proper way to determine the values of A_{wall}.[14] This issue has recently been unequivocally resolved in favor of using the Monte Carlo calculated values[19–21] over the linear extrapolation technique used by Goetsch *et al.* This has led to a change of about 1% in the NIST air-kerma standards for ^{137}Cs and ^{60}Co.[32]

Table I presents values of A_{wall}. The first observation is that the values "measured" using linear extrapolation for the graphite-walled thimble chamber are in good agreement with the Monte Carlo calculated values. Thimble chambers are unusual in this respect. In contrast, for spherical, pancake, and cylindrical chambers with roughly equal diameters and lengths the calculated values and measured values based on extrapolation disagree markedly.[14] Column 4 presents the Monte Carlo values for a spherical graphite-walled chamber of the same wall thickness. These values are up to 1.6% different from those for the thimble chamber (column 3). In Goetsch *et al.*,[1] it is assumed that the A_{wall} values are only dependent on wall thickness and not dependent on detector shape, clearly an incorrect assumption.

Columns 5 and 7 of Table I present the values implied by the data used by Goetsch *et al.* for realistic NE2571 and Exradin A3 chambers, and columns 6 and 8 give the corresponding Monte Carlo values. It is clear that there are substantial differences, especially for the spherical A3 chamber which is the basis of the UWADCL's calibration (up to 2.1%).

How do these incorrect A_{wall} values affect the ^{192}Ir calibration? If all A_{wall} values as a function of beam energy were incorrect by the same amount, there would be no effect. This is not the case and inserting the correct values into Eq. (5) with the UWADCL's A3 chamber's calibration coefficients decreases the implied ^{192}Ir calibration by 0.31%. This implies that the difference between using the correct A_{wall} values and not using A_{wall} values at all is only 0.22% as opposed to the 0.53% difference noted above when using the UWADCL's A_{wall} values. Piermattei *et al.*[33] have also shown that using the correct values of A_{wall} has a significant effect when using Eq. (5) to determine $N_K^{\text{Ir-192}}$.

C. Accuracy of different approaches

1. Graphite-walled chamber

We first present results for a pure graphite-walled thimble chamber because the larger variation in its calibration coefficients with beam quality exposes the accuracy of the underlying theory.

Figure 3 presents N_K' values, [i.e., normalized N_K values; see discussion of Eq. (3)] as a function of average beam energy as well as several values for ^{192}Ir determined using different methods. It is useful that the values for the various spectra plotted as a function of their mean energies lie on the curve defined by the monoenergetic values since this allows us to use our calculations at 146 keV to represent the beam

TABLE I. A_{wall} values for various beam qualities and ion chambers as determined using a Monte Carlo (MC) model of each chamber or the "measured" and extrapolated data for the cylindrical graphite-walled chamber with 0.31 g/cm^2 thick walls (in column 2) applied to all other chambers based solely on the wall thickness [in columns 5 and 7, as done by Goetsch *et al.* (Ref. 1)]. Columns 3 and 4 are Monte Carlo calculations for 0.31 g/cm^2-graphite-walled chambers, a thimble Farmer chamber with a graphite electrode, or a spherical chamber with the same cavity radius as the Exradin A3.

	A_{wall}						
	Graphite, 0.31 g/cm^2			NE2571 Delrin buildup 0.55 g/cm^2		Exradin A3 C-55 0.44 g/cm^2	
Beam quality	"Measured" Cylindrical	Monte Carlo (MC) Cylindrical	Monte Carlo (MC) Spherical	"Measured"[a]	MC	"Measured"[a]	MC
250 kV	0.9991	0.9989	0.9832	0.9984	1.0046	0.9987	0.9781
^{192}Ir	0.9916	0.9930	0.9827	0.9841	0.9896	0.9872	0.9761
^{137}Cs	0.9914	0.9924	0.9850	0.9846	0.9869	0.9877	0.9783

[a]Based on measured data for 0.31 g/cm^2 and applied for different wall thicknesses.

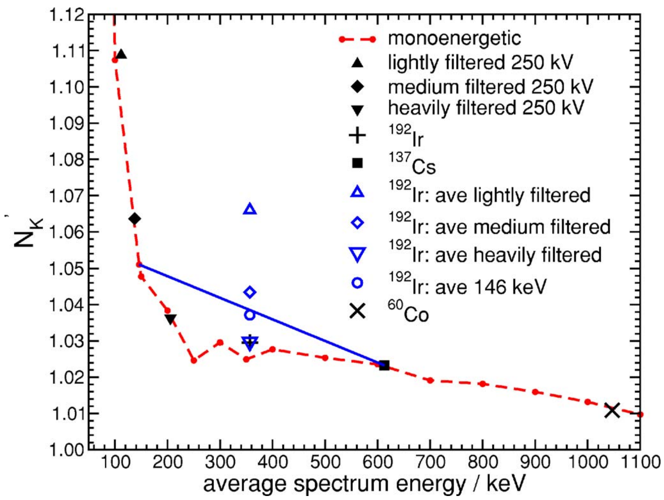

FIG. 3. Calculated N_K' values *vs* average spectrum energy for a 0.6-cm^3 graphite-walled thimble chamber with 0.5 g/cm^2 walls of graphite and a graphite electrode. The open symbols are for the simple average between the ^{137}Cs N_K' value and the values for heavily, medium, lightly filtered x-ray beams and also for a monoenergetic 146-keV beam representing the beam used by Goetsch *et al.*[1] The straight line shows what linear interpolation would give for N_K' values between a 250-kV beam with mean energy of 146 keV and a ^{137}Cs beam.

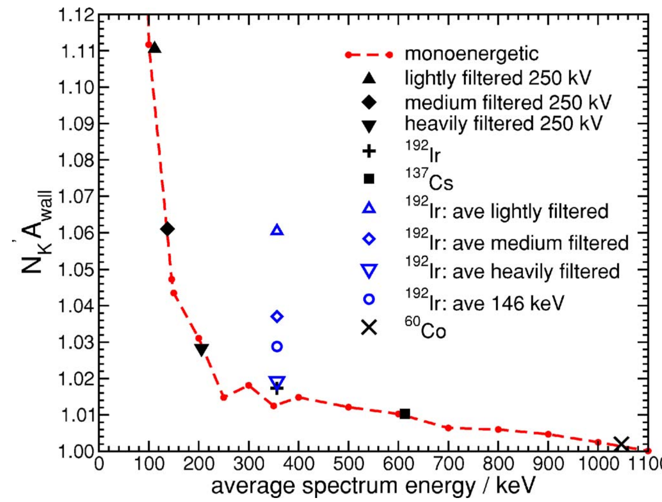

FIG. 4. The same as Fig. 3 but for the product $N_K'A_{\mathrm{wall}}$. Values of A_{wall} are from the Monte Carlo calculations.

used by Goetsch *et al.* (for which we do not have the complete spectrum, but we do know the average energy from their paper).

For this chamber, the calibration coefficient varies dramatically, with N_K' varying by over 7% for 250 kV beams of different filtrations. Correspondingly, the values of the ^{192}Ir calibration coefficient determined by a simple average of one of these 250 kV beams and the ^{137}Cs beam vary considerably. Compared to the value calculated for the ^{192}Ir spectrum, the values determined by averaging range from 3.6% high when using the lightly filtered beam, to within 0.02% when using the heavily filtered beam. The value determined using the 146-keV beam of Goetsch *et al.* is 0.8% high.

If we based the averaging on $1/N_K'$ [Eq. (10)], the ^{192}Ir values would change by no more than 0.02% compared to averaging based on N_K'.

This figure emphasizes the importance of using as heavily filtered a 250-kV beam as possible. This is also true when using the conceptually rigorous method of Eq. (9) since one still needs to estimate N_K' between the two calibrations closest to the 300-keV energy region. The straight line shows the values of N_K' which would be used to interpolate over the region of most interest if a beam with a mean energy of 146 keV is used. These values would clearly be systematically high although the problem would be significantly reduced using a beam with a mean energy of 200 keV.

Figure 4 shows the same data when including the correct (i.e., Monte Carlo) values of A_{wall} in the averaging. In this case, the values determined for ^{192}Ir calibration coefficients are significantly worse (from 4.3% to 0.2% high, and 1.2% high for the 146-keV beam).

From these two figures for the pure graphite-walled chamber we can conclude that the simple averaging technique does not work in principle unless the variation in calibration coefficients is so small that there is no real need for "a method." Figure 3 also makes it clear that when using the more general method of averaging over the N_K values for complete spectra, one must be careful to use an x-ray beam with as much filtration as possible to reduce any interpolation errors.

2. NE2571 chamber

Figure 5 presents data for N_K' as above, but for a realistic model of an NE2571 Farmer chamber with a 0.39 g/cm^2 buildup cap of graphite. Here the chamber response is much flatter but we see that the values for the ^{192}Ir beam are still wrong (although less so) when averaging the ^{137}Cs and 146-keV values. The differences between the Monte Carlo calcu-

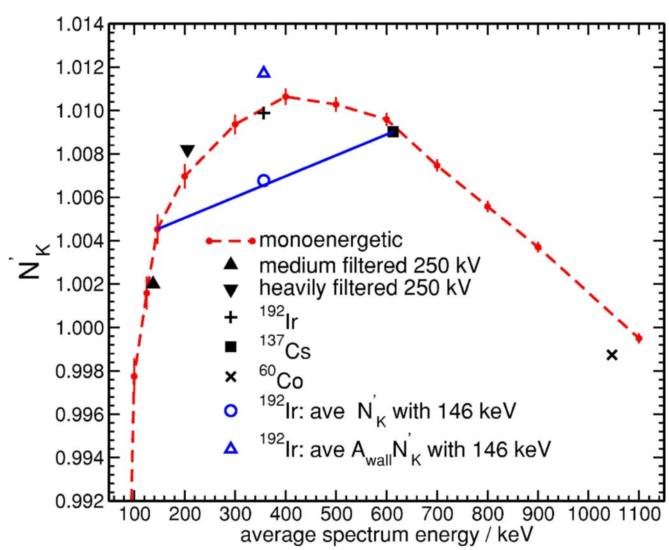

FIG. 5. The same as Fig. 3 but for a realistic NE2571 Farmer ionization chamber with a graphite buildup cap of 0.39 g/cm^2. The open symbols show values by simple averages of N_K' or $N_K'A_{\mathrm{wall}}$ values for ^{137}Cs and 146 keV beams.

TABLE II. Relative difference of averaged $N'_K(^{192}\mathrm{Ir})$ values from the Monte Carlo calculated N'_K values for an NE2571 Farmer chamber with a graphite or Delrin® buildup cap. Each row represents a different way of performing the averaging. The positive and negative signs were used to indicate whether the estimate is lower or higher than the Monte Carlo $N'_K(^{192}\mathrm{Ir})$ value. In row 3, the value of A_{wall} is from the Monte Carlo calculations.

	Relative difference/%	
Averaging method	(Graphite cap)	(Delrin cap)
N'_K	−0.31	−0.35
$(N'_K)^{-1}$	−0.31	−0.35
$N'_K A_{\mathrm{wall}}$	+0.18	+0.27

lated correct value and the averaged values are summarized in Table II. In this case the A_{wall} averaged values are slightly more accurate.

Figure 6 and Table II present the same data for an NE2571 with a Delrin buildup cap. In this case there is little difference using the A_{wall} averaged values. In both cases, averaging N_K or $1/N_K$ makes no observable difference.

3. Exradin A3 chamber

Table III presents similar results for the A3 chamber. Since the response curve is so flat, it is clear that almost any of the methods gives a satisfactory result. The largest discrepancy comes from using Eq. (6) of Goetsch *et al.*, but as shown above, this is mostly from using their values of A_{wall} rather than the correct Monte Carlo values.

4. Using the entire response curve

Table IV compares the Monte Carlo calculated calibration coefficients of various Farmer chambers in an ^{192}Ir beam to the values obtained using the method defined by Eq. (9), using a calculated response curve and weighting the $1/N_K$ values appropriately. As expected, the values are in complete agreement within calculational uncertainties since the equation is exact. However, this does not imply that the technique, as applied in a calibration laboratory, is exact since there is still a need to interpolate the response function over just that region where it is most needed. This region is indicated by the straight lines in Figs. 3, 5, and 6, and can be in error unless highly filtered 250-kV x-ray beams or sophisticated interpolation techniques are used, or the chamber has a very flat response versus beam energy.

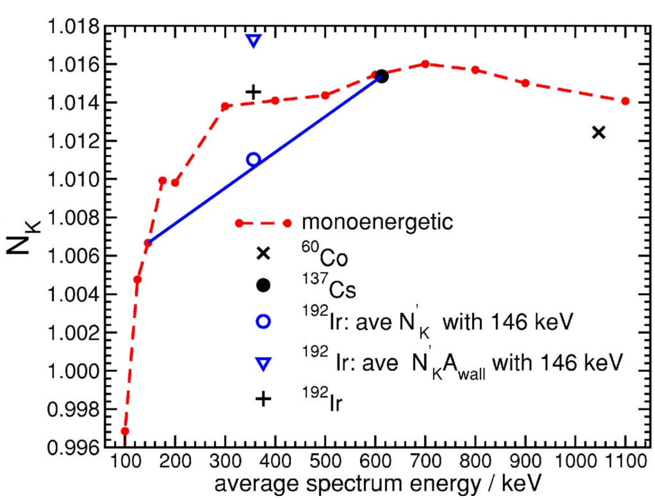

FIG. 6. The same as Fig. 5 but for an NE2571 chamber with a Delrin® buildup cap which is 0.55 g/cm^2 thick.

TABLE III. Same as Table II but for an Exradin A3 spherical chamber. The second column shows the difference for an average of a 146-keV photon beam and a ^{137}Cs spectrum. The third column shows the difference for a medium filtered 250-kV x-ray beam (E_{ave}=137.5 keV) and the ^{137}Cs spectrum. Row 4 uses our values of N'_K with the Goetsch *et al.* formula [Eq. (6)] which implies using their A_{wall} values.

	Relative difference/%	
Averaging method	(146 keV photons)	(250 kV x rays) $\bar{E}$=138 keV
N'_K	−0.11	−0.15
$(N'_K)^{-1}$	−0.11	−0.15
$N'_K A_{\mathrm{wall}}$	+0.11	+0.19
Equation (6)	+0.42	+0.38

IV. SUMMARY AND CONCLUSIONS

If averaging is used to determine the calibration coefficient for a chamber in an ^{192}Ir beam one should, in principle, average $1/N_K$ rather than N_K, even though this makes no practical difference.

There is no justification in using A_{wall} weighting in the averaging. For the case of a pure graphite-walled thimble chamber this can cause an error of 0.7%, but for realistic chambers the error is much less. More importantly, the techniques used by Goetsch *et al.*[1] to determine A_{wall} were faulty as described in Sec. III B and can lead to systematic inaccuracies in A_{wall} values of 2% but an error of only 0.3% in the values of ^{192}Ir calibration coefficients. Given these two observations, and the fact that determining appropriate A_{wall} values is an extra and unnecessary step, it is concluded that they should not be used in the averaging procedure.

Overall, the averaging techniques all depend critically on using a chamber with a flat response and/or a very heavily filtered 250-kV x-ray beam so that the variation in chamber response is as small as possible, in which case, all of the techniques are adequately accurate.

Although the technique of using a complete response curve as a function of beam energy along with the kerma-

TABLE IV. $N'_K(^{192}\mathrm{Ir})$ values obtained using the K_{air} weighted averaging procedure from Eq. (9) for different 0.6 cm^3 graphite-walled thimble chambers irradiated by an ^{192}Ir HDR brachytherapy source. The all graphite chamber has 0.5 g/cm^2 thick walls.

	N'_K All graphite	N'^{NE2571}_K Graphite cap	N'^{NE2571}_K Delrin cap
Monte Carlo	1.0296	1.0099	1.0140
Averaging $(N'_K)^{-1}$	1.0292	1.0098	1.0136

weighted average of the responses is, in principle, exact, in practice it is also subject to the above concerns. If the chamber has a sufficiently flat response curve, then there is little to be gained from the extra effort of this technique and a simple averaging of N_K values is adequate (consistent with the observations of van Dijk[12]).

Given that the values of the ^{137}Cs standard at NIST have recently changed[32] by about 1%, it would be worthwhile to reevaluate the ^{192}Ir calibrations being disseminated in North America. Given all of the issues raised here, it may also be time to establish a primary standard for air kerma in an ^{192}Ir beam since Borg *et al.*[3] have shown that Spencer-Attix cavity theory holds with adequate accuracy for these beams, thereby making a primary standard feasible.

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