Changes in ^{60}Co air-kerma standards: the rationale for change and the impact on clinical practice

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Primary air-kerma standards for ^{60}Co beams are based on graphite-walled cavity ion chambers. Most national air-kerma standards remained the same since the late eighties when they changed by about 1% due to changes in the internationally agreed underlying physical data. During the nineties there was concern expressed that the measurement/extrapolation method used to determine K_{wall}, the correction for attenuation and scatter in the walls of the ion chamber, was wrong. The present consensus at the international level is that Monte Carlo calculations of K_{wall} for the graphite-walled cavity-ionization chambers are more accurate than the linear extrapolation technique that was used in establishing the existing standard. . With the advent of clear experimental evidence from the PTB in 2001 that the measurement/extrapolation method was incorrect, many standards labs are re-considering their correction factors. Re-evaluations at NIST indicate that their ^{60}Co air-kerma standard will increase by about 0.9%, which they plan to implement during the year 2003. At NRCC, corrections resulting from calculated values of K_{wall} were already implemented.

A change of air-kerma standard by NIST affects the calibration chain from the Primary standards lab through the Accredited Dosimetry Calibration Laboratories (ADCLs) to the user. This is because the ADCLs maintain high-quality secondary standards that have NIST traceable calibration coefficients. They use these secondary standards to establish air-kerma standards in their own beams. If the NIST standard for air-kerma rate increases, then the secondary standards of the ADCLs will also increase. This in turn will increase the air-kerma calibration coefficient of the user's ionization chamber by about 0.9%.

If absorbed dose is determined using the TG-21 protocol then an increase of N_K by about 0.9% will increase the absorbed dose determination by about 0.9%. The change in N_K does not affect dose determination using the TG-51 protocol because it based on an absorbed dose-to-water standard. The AAPM published the TG-51 protocol nearly three years ago; however, only ~35% of US radiation therapy facilities have reported making the transition (RPC data). Depending on the beam modality, energy and instrument type, differences between the two protocols have been observed to lie between 1 and 3%. Part of this difference arises from a change of the calibration standard from air-kerma to absorbed-dose-to-water. When the NIST air-kerma standard is increased by about 0.9%, differences between the two calibration protocols will be reduced by this amount. Medical physicists are advised to convert to the TG-51 protocol for several reasons: (1) RPC data show that fewer errors are made in implementing TG-51, (2) implementation of a calibration protocol based on an absorbed dose-to-water standard will make US physics practice consistent with most of the rest of the world.

At the conclusion of this course the attendee should be able to understand

1. How air-kerma standards are established.
2. Rationale for changing the air-kerma standards at NIST
3. How such a change will affect the standards maintained at the ADCLs
4. Effect on dose determination using the TG-21 or TG-51 protocol
5. Rationale for converting to the TG-51 protocol

Changes in ^{60}Co standards: the rationale for change

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Introduction

When a primary standards laboratory determines the air-kerma in a ^{60}Co beam, the following equation is used:

$$K_{\rm air} = \frac{Q_{\rm gas}}{m_{\rm air}(1-\overline{g}_{\rm air})} \left(\frac{W}{e}\right)_{\rm air} \left(\frac{\overline{L}}{\rho}\right)^{\rm wall}_{\rm air} \left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)^{\rm air}_{\rm wall} K_h K_{\rm wall} K_{an} K_{\rm comp} K \qquad ({\rm Gy}), \qquad (1)$$

where $Q_{\rm gas}$ is the charge released in the air of mass $m_{\rm air}$, $\overline{g}_{\rm air}$ is the average fraction of the energy of an electron lost in radiative events while slowing in air, $\left(\frac{W}{e}\right)_{\rm air}$ is the energy lost in dry air per coulomb of charge released, $\left(\frac{\overline{L}}{\rho}\right)^{\rm wall}_{\rm air}$ is the Spencer-Attix collision mass stopping-power ratio for the wall material to dry air, $\left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)^{\rm air}_{\rm wall}$ 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, $K_{\rm wall}$ corrects for the attenuation and scatter in the chamber wall, K_{an} corrects for the axial non-uniformity due to the point source nature of the beam instead of the photon beam being parallel, $K_{\rm comp}$ is a correction for the composite, *i.e.*, non-uniform nature (if any) of the wall material and K includes various corrections for other non-ideal conditions (*e.g.,* corrections for stems, central electrodes of different material from the wall, radial non-uniformity of the beam, etc). For a detailed discussion of this equation and its derivation, see, *e.g.,* reference.[1]

For the graphite-walled ion chambers used in standards laboratories, by far the largest correction in eqn(1) is $K_{\rm wall}$. Traditionally $K_{\rm wall}$ has been determined by adding a series of extra shells around the ion chamber and determining the response as a function of wall thickness. In a ^{60}Co beam the response is remarkably linear as a function of the wall thickness and so it has been assumed that one could extrapolate linearly back to zero wall thickness in order to determine the correction for attenuation and scatter in the wall (with an additional correction to take into account the centre of electron production, $K_{\rm cep}$).

The $K_{\rm wall}$ problem

In 1990 this linear extrapolation method was shown not to work. For example the measured values for spherical and near-spherical cylindrical chambers tended to be low by 0.8% to 1.0% compared to Monte Carlo calculated values.[2] Bielajew demonstrated that under some simplifying assumptions and for a spherical chamber, the extrapolation is non-linear (but usually only where the wall is so thin that full buildup is not achieved and hence measurements are not helpful).[3] His theory gave good agreement with Monte Carlo calculated values of $K_{\rm wall}$.

However, those working in standards laboratories were reticent to make the required change because it appeared to cause the differences between various standards to become much worse (since the change in $K_{\rm wall}$ ranged from −0.5% for pancake-shaped ion chamber standards to +1.0% for spherical ion chambers). In addition, there was some reluctance to base the change on one set of calculated values or to make a change without direct experimental verification of the Monte Carlo calculations.

The K_{an} problem

One part of the problem was resolved by the observation that another correction factor, *viz.*, K_{an}, the correction for the point of measurement in a field with an axial non-uniformity, was also incorrectly assessed in a few cases (ranging from +0.5% to +1.0% for those cases not using unity previously).[4] The net effect of applying both changes to 8 standards was to increase the average air-kerma standards by 0.6% at the 5 National Metrological Institutes (NMIs) analyzed.[4] In a more recent analysis of many more NMI's standards (16 in total) and using the EGSnrc Monte Carlo code,[5] the average increase was found to be 0.8%. Furthermore, the scatter in the new air-kerma standards is only marginally worse than for the scatter using the linearly extrapolated $K_{\rm wall}$ values.[6]

After the re-analysis, the primary standard of NRC, the Canadian NMI at which I work, was one of the outliers. We had been using the Monte Carlo calculated values of $K_{\rm wall}$ and K_{an} since 1990 and thus our standard did not increase as the other standards did. However, in a pair of recent Monte Carlo studies it has been realized that the NRC primary standard needs a rather large correction (+0.4%) because of a polystyrene insulator.[7,8]

Experimental verification

In the last few years there have been a variety of experimental results in support of the Monte Carlo calculated $K_{\rm wall}$ values. Laitano et al[9] compared measurements of response vs wall thickness for separate parts of the chamber and demonstrated agreement with the Monte Carlo calculated $K_{\rm wall}$ values within 0.2%. However, the procedure used was quite complex. Shortt et al[10] have a more direct approach where they measure the response of a spherical ion chamber as a function of wall thickness (see fig 1). Using a ^{137}Cs beam allowed them to go to thinner walls and they see the non-linearity. However, in my opinion, their entire argument is dependent on the point with the thickest wall (without which all of the other points lie on a perfect straight line) or on the point with the thinnest wall (with a 0.6% correction for scatter from materials near the chambera). When fitting all 9 points the linear hypothesis is ruled out by a χ^2 with only a 10% probability and thus the argument is not completely persuasive but does strongly suggest non-linearity.

In another approach, McCaffrey et al[11] have measured the the response of NRC's plane-parallel graphite-walled ion chamber, called the Mark IV, as a function of angle as it is rotated in the beam. The response varies by about 8% and is reproduced by Monte Carlo calculations within 0.3%, including a shoulder in the response at about 85 degrees (see fig 2). The variation in response is almost entirely due to the change in the wall attenuation and scatter and hence the good agreement between calculation and measurement is a strong indicator that the calculated $K_{\rm wall}$ values are accurate. In addition, McCaffrey et al compared

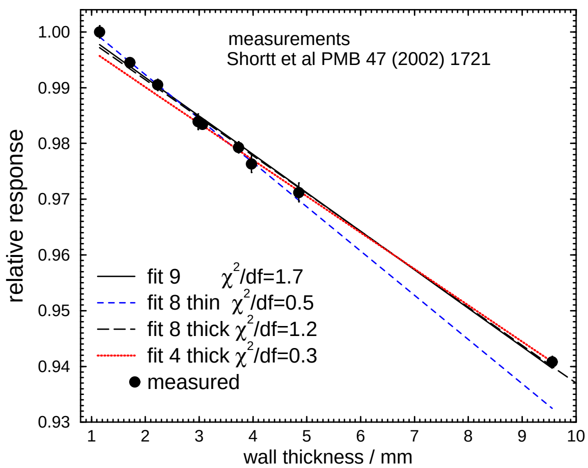

Figure 1: Measured data of Shortt et al[10] for response vs wall thickness of a spherical walled chamber in a ^{137}Cs beam. Also shown are linear fits including various numbers of data points in the fit along with the χ^2 per degree of freedom for each fit. In the original paper, only the fit to the thickest 4 points was included.

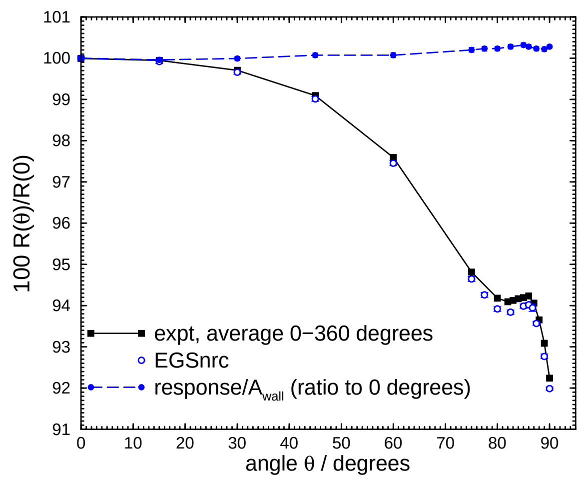

Figure 2: Measured (square symbols) vs. EGSnrc-calculated (open circles) responses of the Mark IV plane-parallel chamber as a function of angle. The measurements were taken in all four quadrants and averaged. The residual 0.28% variation in response/$A_{\rm wall}$ has been shown to be due to point of measurement effects and does not exist if a parallel beam is used in the calculations.

the absolute measured air-kerma rate using two different shaped ion chambers (the pancake Mark IV chamber and the cylindrical 3C chamber). When linear extrapolations of the measured responses as a function of wall thickness were used to determine the values of $K_{\rm wall}$, the difference in the measured air-kerma rate was nearly 2%. When the Monte Carlo calculated values of $K_{\rm wall}$ were used, the absolute measured air-kerma rates agreed within 0.12%. This nearly 2% difference comes about because the Monte Carlo $K_{\rm wall}$ is much larger than the measured-extrapolated value for the cylindrical chamber, whereas for the pancake chamber, the non-linearity causes the calculated $K_{\rm wall}$ factor to be less than the measured-extrapolated value for the pancake chamber.

However, Büermann et al have provided the most definitive results proving that the linear extrapolation method is incorrect. They have performed a very straightforward but clever experiment[12,13] with a clearcut result. For a variety of chambers, they measured the response vs wall thickness for the same chamber as they placed the ion chamber at different angles in a ^{60}Co or ^{137}Cs beam. In this way, almost all of the factors in eqn(1) are the same (at least to first order). Thus the extrapolated response at zero wall thickness should be the same, independent of what angle the beam is at. However, as fig 3 makes clear, this is not the case for this particular chamber (a cylindrical chamber with an inner diameter and length of 5 cm). Figure 4, also based on the data of Büermann et al,[13] shows that the same sort

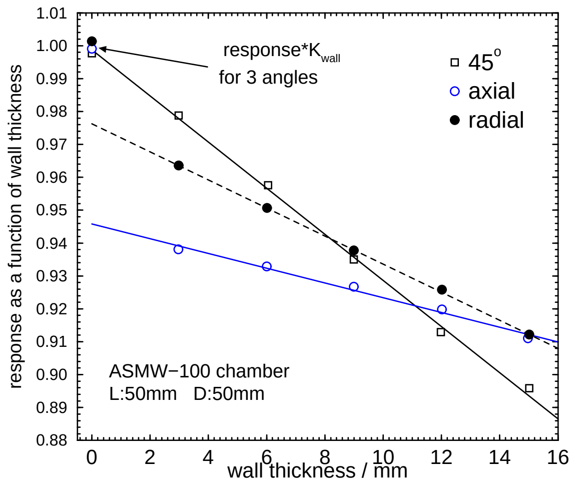

Figure 3: Response as a function of wall thickness for the ASMW chamber set at different angles in a ^{60}Co beam. The lines are linear fits to the data and differ by 5.6% for 0 wall thickness. These lines should all extrapolate to the same value if the linear extrapolation were valid. In contrast, the measured responses for the thinnest wall, multiplied by the Monte Carlo calculated value of $K_{\rm wall}$ all have nearly the same value, shown by the symbols at zero wall thickness. Based on the data of Büermann et al,[12] with permission.

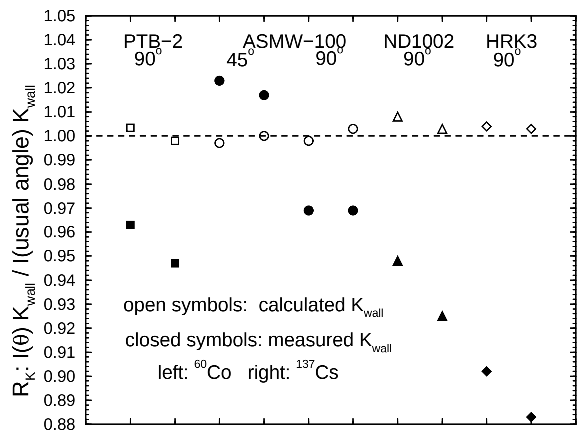

Figure 4: The ratios of the ionization currents corrected for wall effects at different angles of radiation incidence and the values obtained at the usual angle of incidence for that chamber. The ratios obtained using calculated $K_{\rm wall}$ values are shown as open symbols and those using measured-extrapolated values as closed symbols. The first value for each combination of chamber and angle is for a ^{60}Co beam and the second for ^{137}Cs. For consistent $K_{\rm wall}$ values, the ratios should be unity, corresponding to extrapolating to the same value in figures corresponding to fig 3 for each chamber and beam.

of results occur for chambers of many different shapes, with discrepancies as large as 11% using the linear extrapolation data whereas the Monte Carlo calculated values lead to highly consistent results (PTB-2, thimble 20×10 (length × height in mm); ASMW-100, cylindrical 50×50; ND1002, pancake 4×23; HRK3, pancake 4.5×44).

What does this mean?

As a result of the clear experimental demonstration of the need for using calculated values of $K_{\rm wall}$, the various primary standards labs have undertaken to evaluate the values appropriate for their chambers. This has led to a flurry of activity with many laboratories using codes such as PENELOPE, MCNP and ITS to confirm the values calculated at NRC. Specifically Seltzer and Bergstrom at NIST have done a very thorough re-evaluation and independent calculations for all the Monte Carlo calculated factors needed for the NIST cavity-chamber-based air kerma standards.[14] Their final conclusion is that the NIST primary standard for air kerma in a ^{60}Co beam must increase by 0.88% as a result of using their Monte Carlo calculated values of K_{wall} and increase by another 0.17% as a result of the re-evaluations of other factors (stopping-power ratios, mass energy absorption coefficients etc). Thus the NIST air-kerma standard for a ^{60}Co beam increased by 1.0105% effective July 1, 2003.

In a recent NRC paper,[8] the uncertainties associated with the use of calculated correction factors were estimated, including the uncertainties due to the uncertainties in the underlying cross-sections, which have very little effect on the K_{wall} correction factor. That same paper re-evaluated the various corrections needed for the Canadian primary standard of air kerma in a ^{60}Co beam and found that an overall increase of 0.54% is needed.

The ^{60}Co air-kerma standard in Canada has been shown to be 0.61% larger than that in the US.[15] As a result of the changes noted above, the Canadian air kerma standard will only be 0.10% larger than the NIST standard, well within the stated uncertainty of the comparison of 0.4%.

Clinical implications

These changes mean that the air-kerma calibration factors supplied by NIST and NRCC will change and thus will have a direct effect on clinical dosimetry based on the TG-21 protocol[16] since it starts from an air kerma calibration factor. But for clinical dosimetry based on the TG-51 protocol[17] there will be no effect since it uses absorbed-dose calibration factors. The implications are discussed more fully in other parts of this refresher course.

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Changes in Co-60 air-kerma standards: the impact on the Accredited Dosimetry Calibration Laboratories

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The consensus at the international level is that Monte Carlo calculations of K_{wall} for the graphite-walled cavity ionization chambers are more accurate than the linear extrapolation technique that is currently used. NIST has done extensive Monte Carlo calculations of K_{wall} for its suite of spherical graphite-walled ionization chambers. Based upon these calculations, NIST has revised the US Primary Standard for air-kerma rate. This revision will result an increase in the values of air-kerma calibration coefficient of all ionization chambers by about 0.9% in a Co-60 beam.

The Accredited Dosimetry Calibration Laboratories (ADCLs) maintain high quality secondary standards that have NIST traceable calibration coefficients. They use these secondary standards to establish air-kerma standards in their own beams. If NIST standards for air-kerma rate increases by about 0.9% then the secondary standards of the ADCLs will also increase by the same amount. The ADCLs have already obtained new measured air-kerma calibration coefficients from NIST for their secondary standards and have established new air-kerma standards at their own Co-60 beams. So, when users send their ionization chambers to the ADCLs, they will see an increase in air-kerma calibration coefficient of their ionization chambers by about 0.9%. N_{gas} is obtained from N_K so that a change in N_K carries through to a change in the dose determined using TG 21. Since the value of N_{gas} is directly proportional to the value of N_K, an increase of N_K by about 0.9% will also increase the value of N_{gas} by about 0.9%. This in turn will increase the dose determined using the AAPM TG-21 protocol by about 0.9%. Thus, a change by NIST of the air-kerma standard affects the entire calibration system, from the primary standards lab through the ADCLS to the user.

Implementation of the changes in the value of K_{wall} for various ionization chambers does not affect the absorbed dose to water standard, D_w, established by NIST. This is because the NIST primary standard of absorbed dose to water is based on calorimetric method. As a consequence, the D_w standard established at the ADCLs also will not change. Therefore, the absorbed dose to water calibration coefficient, $N_{D,w}$, provided by the ADCLs to the users for various ionization chambers will not change. Absorbed dose to water, determined using the AAPM TG-51 protocol will therefore remain unchanged as a result of the changes in K_{wall}.

The ADCLs maintain a library of values of $N_{D,w}/N_K$ for various cylindrical and plane-parallel ionization chambers. This is done to study the performance history of all ionization chamber types. An increase in the value of N_K will decrease the value of $N_{D,w}/N_K$ by the same amount. Depending on the ratio of calibration factors, $N_{D,w}/N_K$, supplied by a calibration laboratory, the observed change at C0-60 may become the most significant contributing factor to any differences that are observed in high energy photon beam calibrations based on standards of absorbed dose to water. Studies have shown that the values of $N_{D,w}/N_K$ for various ionization chambers types maintained by the US ADCLs are about 1% higher than those maintained by the other ADCLs across the world. Therefore, the adjustment of K_{wall} by NIST will bring the dosimetric results observed in the US closer to the rest of the world.

Changes in ^{60}Co air-kerma standards: the impact on clinical practice.

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When the US national air-kerma standard changes, the adjustment will raise the air-kerma calibration coefficient for ionization chambers by about 0.9%. Correspondingly, measurements of dose in megavoltage beams, when based on an air-kerma calibration coefficient (N_K), will increase by the same amount. The AAPM calibration protocol published in 1983 (the "TG-21 protocol") is based on an air-kerma calibration coefficient that is used to determine N_{gas}. Consequently, calibrations based on the TG-21 protocol will yield measurements of absorbed dose that are 0.9% greater than before, and will result in a downward adjustment of dose per monitor unit.

The current AAPM protocol (the "TG-51 protocol") is not based on an air-kerma standard but requires that calibration instruments have a dose-to-water calibration coefficient ($N_{D,w}$). The dose-to-water calibration standard was determined at NIST by independent methods, and will not change when the air-kerma standard changes. As a result, megavoltage calibrations made using the TG-51 protocol will not be affected.

This means, however, that the relationship between TG-51 and TG-21 calibrations will change. Several publications have shown that from both theoretical and experimental perspectives, calibrations made following the TG-51 protocol yield doses in water that are somewhat larger than those made using the TG-21 protocol.[1-3] For photon beams and low-energy electrons, the difference is about 1%, while for higher energy electrons, the difference is closer to 2%.

The implementation of the K_{wall} correction will reduce this difference by about 1%, essentially eliminating the difference between the two calibration protocols for photon beams and for low-energy electron beams.

What does this mean for the practicing clinical physicist?

1. Calibrations performed using the AAPM TG-51 calibration protocol will not be affected by the change to the air-kerma standard.

2. Calibrations performed using the TG-21 protocol will change by about 1%, once a new N_K calibration coefficient is assigned to the calibration instrument.

3. Much of the reported difference between TG-21 and TG-51 will disappear after the air-kerma revision is implemented.

4. This is not a good reason to postpone converting to TG-51.

- The TG-51 protocol is arguably easier to implement. RPC data show, anecdotally at least, that when differences between the two protocols exceed the expected range, the errors more often were made with the TG-21 calibration.

- The TG-51 protocol, as it is based on a dose-to-water standard, conforms more closely to calibration protocols used elsewhere throughout the world.
- Use of the TG-51 protocol may lead to greater uniformity in delivered doses among institutions.

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