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The 2003 revision of the NRC standard for air-kerma in a ^{60}Co beam

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Abstract

The National Research Council of Canada's standard for air-kerma in a ^{60}Co beam has remained fixed since 1990. As a result of a re-evaluation of various correction factors and an effort to make a realistic assessment of the uncertainties on Monte Carlo calculated correction factors, the NRC standard changed on Oct 1, 2003. The overall increase in the standard is 0.59% and the overall uncertainty on the standard has been reduced to 0.28%. This is a correction in the factors used, not the measurement data, and thus ^{60}Co air-kerma calibration factors received from NRC prior to Oct 1, 2003 can be converted to values consistent with the new standard by multiplying the old factor by 1.0059. The present change has no impact on either the absorbed dose to water standards at NRC or the air-kerma standards based on free-air chambers. On the other hand, the change directly affects the standards in ^{137}Cs beams which are obtained using chambers calibrated using the ^{60}Co standard. A result of the changes at NRC and related changes at NIST is that the ratio of the ^{60}Co air-kerma standards at NRC and NIST is now 1.0015, well within the uncertainties of the comparison. This compares well to the previous value of 1.0061.

I Introduction

For more than 10 years, scientists at NRC have pointed out problems with the techniques used to determine several correction factors needed to establish primary standards of air kerma in a ^{60}Co beam.[1–6] In particular, the K_{wall} correction for attenuation and scatter in the walls of the primary standard cavity ion chamber, and/or K_{an}, the correction for the axial non-uniformity in the beam, require changes at many laboratories. Following a recent flurry of activity which confirmed these problems,[7–10] many other National Metrological Institutes are changing their standards for air kerma in a ^{60}Co beam. NRC requires no significant change regarding K_{wall} and K_{an} since these changes were made at NRC in 1990.[11] The changes at the other laboratories are expected to raise the average air-kerma standard by about 0.8% and thus NRC's standard would appear to become an outlier since it was in good agreement with most other standards before they made these changes.[6]

As part of another study, it was discovered several years ago that the polystyrene insulator in the NRC 3C standard ion chamber has a considerable effect on the chamber response[12] and in more recent and detailed calculations, it was found that the correction to account for this should be $K_{\text{comp}} = 1.0046$.[13] On further investigation, it was found that prior to 1990, there was a correction included for this effect in the Canadian standard (1.002) but, in that the 1990 revision, it had been decided not to include this correction.

It was also recognized that the dependence on calculated correction factors made it necessary to have a more rigorous uncertainty analysis for these factors. This has been provided in a recent study[13] and at the same time, minor changes to various correction factors have been found necessary.

The purpose of this report is to document the values and uncertainties for the various correction factors and quantities used to determine the Canadian primary standard for air kerma in a ^{60}Co beam, effective Oct 1, 2003. The overall change (an increase of 0.59%) is not very big but it does mean that the NRC standard is expected to be in good agreement with the revised values of air kerma at most other National Metrological Institutes. However, a detailed analysis of the new status will require waiting for the other standards to be re-evaluated, with the exception of that of the USA, which has already formally declared its new standard. These comparisons are discussed in section V.

II Definitions

When using a cavity chamber standard, the air kerma, $K_{\rm air}$, is established at a point in a ^{60}Co beam using:[14,15]

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

where:

- $Q_{\rm gas}$ is the charge released in the air in the cavity of the primary standard chamber, the 3C,
- $m_{\rm air}$ is the mass of dry air that would fill the cavity in the 3C under reference conditions,
- $\overline{g}_{\rm air}$ is the fraction of the energy of a ^{60}Co-generated 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 mass collision 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 which accounts for the changes in stopping-power ratio, the value of $\left(\frac{W}{e}\right)$ and the mass of the air in the chamber when the air is humid and not dry,[16]
- $K_{\rm wall}$ corrects for the attenuation and scatter in the chamber wall,
- $K_{\rm an}$ corrects for the axial non-uniformity due to the point source nature of the beam,
- $K_{\rm comp}$ is a correction for the composite, *i.e.*, non-uniform nature of the wall material (if any),
- $K_{\rm stem}$ corrects for the scatter from the ion chamber's stem,
- K includes corrections for other possible non-ideal conditions (*e.g.*, radial non-uniformity of the beam, etc).

To measure the value of $Q_{\rm gas}$ one must correct the measured charge with a saturation correction, $K_{\rm sat}$, to account for incomplete collection of the charge released in the ion chamber and also take into account any polarity correction, $K_{\rm pol}$. Shortt and Ross have given a detailed description of the Canadian primary standard as of 1986[14] although it was revised in 1990.[11]

In the current revision of the standard, no changes are made to the quantities $m_{\rm air}$ or $Q_{\rm gas}$, or in the correction factors $K_{\rm sat}$, $K_{\rm pol}$, $K_{\rm stem}$, K_h, $\left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)^{\rm air}_{\rm wall}$ and $\left(\frac{W}{e}\right)_{\rm air}$. In other words, the current revision is not based on new measurements but is based solely on new values of various correction factors.

III New Values of correction factors

Table I presents a summary of the correction factors which are changing at this time and the following sections discuss each in turn.

Table I: Summary of the changes to the Canadian primary standard for air kerma based on Monte Carlo calculations. Values from ref[13] (but note that the wrong total was given in the reference (0.54% rather than the correct 0.59%) and an erratum is being submitted). One standard deviation uncertainties are shown in brackets.

Quantity	1990 Value	New value	% Change
$K_{\rm wall}$	1.0218	1.0220(3)	+0.02%
$K_{\rm an}$	0.9999(6)	1.0004(6)	+0.05%
$\left(\frac{\overline{L}}{\rho}\right)^{\rm graphite}_{\rm air}$	1.0005	1.0010(65)	+0.05%
$K_{\rm comp}$	1.000	1.0046(17)	+0.46%
1.0 - $\overline{g}$	0.9968	0.9969(1)	+0.01%
	Overall change		+0.59%

III.A $K_{\rm wall}$

NRC used calculated values of $K_{\rm wall}$ in 1990 and thus the change at this time is rather small. The calculations in 1990 were done for a parallel beam of 1.25 MeV photons using EGS4. Using EGSnrc instead of EGS4 for a parallel beam of 1.25 MeV photons leads to no change in K_{wall}. Doing the calculation for a realistic ^{60}Co spectrum calculated for our calibration unit[17] instead of a 1.25 MeV monoenergetic beam, both with a parallel beam, increases K_{wall} by 0.12%. This is almost exactly offset by a 0.11% decrease going from a parallel beam to a point source. Note that in ref[13] the footnote to Table II about K_{wall} both (a) reverses the signs of the changes and (b) reports results which are not properly additive so they are not completely consistent with the values in the present table (*i.e.*, the previous result for the spectral effects is for a point source beam and the result for the point source vs parallel beam is for the realistic spectrum, and the EGSnrc vs EGS4 result is for the point source with the realistic spectrum).

III.A.1 Angular effects on K_{wall}

Takata et al have recently pointed out that the value of K_{wall} is sometimes very sensitive to the angle of the beam with respect to the ion chamber.[18,19] We have done calculations for the 3C chamber and find that between 90 and 91 degrees the value of K_{wall} drops by 0.1% and the drop between 90 and 95 degrees is about 0.20% with a slight increase (0.05%) for angles between 85 and 90 degrees. The asymmetry about 90 degrees is caused by the fact that the large electrode does not extend the length of the cavity. If the electrode is extended to the top of the cavity in the calculations, the asymmetry disappears although there is still a small (0.05%) increase near 90 degrees. The reproducibility of the charge measurement with the 3C chamber for repeated setups is 0.04%.[20] We assume that the uncertainty due to the alignment is contained within this uncertainty. However, if we were to assume a very conservative estimate of 1 degree as the uncertainty on the alignment, this would lead to a 0.1% uncertainty on the calculated value of K_{wall}. Although this is much greater than the stated uncertainty on K_{wall} of 0.03%, this would still only raise the overall uncertainty on the air-kerma standard from 0.28% to 0.29%.

III.B K_{an}

The statistical uncertainties on calculated K_{an} values are much larger than for K_{wall} values and thus small changes due to the spectrum or algorithm used are hard to detect.[13] There is a very small increase in the value of K_{an} being used, which is within the statistical uncertainty of the previous calculation (0.06%).

III.C $\left(\frac{\bar{L}}{\rho}\right)^{\mathrm{graphite}}_{\mathrm{air}}$

The graphite to air stopping-power ratio used for the standard in 1990 was calculated using ICRU Report 37 stopping powers[21] with a density effect corresponding to a graphite density of 1.7 g/cm^3 and a threshold value of $\Delta = 10$ keV. The choice of ICRU Report 37 stopping powers had been agreed to by the international community of standards laboratories and was responsible for a 0.92% decrease in the exposure standard at that time.

At this time we continue to use the same recommended stopping powers to calculate the stopping-power ratio despite the fact that there is a strong indication from measurements with higher-energy electrons[22,23] that one should use the density effect for the grain density of graphite (2.265 g/cm^3). Using this density effect would lead to a 0.23% decrease in the stopping-power ratio.[13]

There have been several improvements in the calculation of stopping-power ratios since the value used in 1990 was calculated (originally done in 1985[1]). It has been shown[13] that use of a realistic ^{60}Co spectrum instead of a mono-energetic 1.25 MeV spectrum increases the value by 0.14%. Using a proper regeneration technique decreases the value by 0.04%.[13] Using a more realistic value of $\Delta = 19$ keV for the NRC 3C chamber[13] leads to a 0.07% decrease and using EGSnrc instead of EGS4 increases the value by 0.02%. Fortunately these changes mostly cancel each other and the overall change is only 0.05%.

As discussed elsewhere,[13] strictly speaking the change in the stopping-power ratio should not affect the air-kerma standard because what enters the equation is the product $\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{graphite}}_{\mathrm{air}} \left(\frac{W}{e}\right)_{\mathrm{air}}$ and this is determined independently of these calculations. Nonetheless, we will follow normal practice and utilize our best estimate of $\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{graphite}}_{\mathrm{air}}$ and the adopted value of $\left(\frac{W}{e}\right)_{\mathrm{air}}$.

III.D K_{comp}

Prior to 1990 the Canadian standard included a correction factor of 1.002[14] (now called K_{comp}) to account for the polystyrene insulator in the chamber. However, in the 1990 revision of the standard this correction was not used. As mentioned in the introduction, more recent work[12,13] indicates that this correction is quite large and has been assigned a value of $K_{\mathrm{comp}} = 1.0046$.

III.E 1.0 - $\overline{g}$

The factor $\overline{g}$ has changed very slightly based on new calculations[12] using the EGSnrc code system and the ICRU Report 37 stopping power data.

IV Uncertainties

A recent NRC study[13] has made realistic estimates of the uncertainties of the various Monte Carlo calculated correction factors. These include estimates of the uncertainties due to cross section uncertainties. The most significant uncertainty is that for the K_{comp} correction because this is a relatively large correction and its calculation is directly dependent on knowledge of the cross sections of the materials involved. For the primary standards in most other National Metrological Institutes this would be a much smaller correction and correspondingly smaller uncertainty. These overall uncertainties are shown in table I. Note that the uncertainty on the stopping-power ratio does not affect the final uncertainty of the standard directly.

IV.A Overall uncertainty analysis

Table II summarizes all the values used in establishing the Canadian primary standard for air kerma in a ^{60}Co beam using the NRC 3C standard. Values not reported above are taken from the most recent NRC comparison of this standard with the BIPM.[20]

The previous overall standard uncertainty on the air-kerma rate[20] was 0.32%. With this new analysis, the overall uncertainty is reduced slightly to 0.28%. The major contribution to this uncertainty is from the correction for the insulator material (0.17%) but even without this correction the overall uncertainty would still be 0.22%

V Comparisons with other primary standards

The NRC air-kerma standard has been compared to the primary standards of several other National Metrological Institutes[20,24–27] and the results of all these comparisons will be affected by the change reported here. In many cases these other standards are also undergoing changes. However, NIST has already declared the value of their new standard and thus it is possible to update the results of the previous comparison.[24]

In the previous comparison[24] the reported ratio of the NRC to NIST air-kerma standard at ^{60}Co was 1.0061. NIST has increased their ^{60}Co standard by 1.05%, mostly as a result of an increase in their value of K_{wall}.[10] In combination with the present 0.59% increase in the Canadian standard, this implies that the new ratio of the standards is 1.0061*1.0059/1.0105 = 1.0015, *i.e.*, the NRC standard is 0.15% larger than that of NIST. This is well within the uncertainty of the comparison and well within the stated uncertainties of each standard.

The BIPM standard has not undergone any changes recently, and it may still do so. Nonetheless it is valuable to revise the comparison between NRC and the BIPM since this

Table II: Summary of values and their relative standard uncertainties in current use with the NRC primary standard for air kerma in a ^{60}Co beam. All uncertainties not reported above come from the latest NRC-BIPM comparison.[20] The two uncertainties reported correspond to the type A (s_i) and type B (u_i) uncertainties.

Quantity	Value	Uncertainty(%)	
		s_i	u_i
Physical constants			
dry air density$^{a)}$/kg m^{-3}	1.2929	-	0.01
$\left(\frac{\mu_{\text{en}}}{\rho}\right)^{\text{air}}_{\text{gr}}$	0.9987	–	0.10
$\left(\frac{\overline{L}}{\rho}\right)^{\text{graphite}}_{\text{air}}$	1.0010	–	0.12$^{b)}$
$\left(\frac{W}{e}\right)_{\text{air}}$/ J C^{-1}	33.97		
1.0 - $\overline{g}$	0.9969	–	0.01$^{c)}$
Correction factors			
K_{sat}	1.0016	0.03	0.03
K_h	0.9970	–	0.05
K_{stem}	0.9960	0.02	–
K_{wall}	1.0220	–	0.03
K_{comp}	1.0046	0.03	0.17
K_{an}	1.0004	0.04	0.05
Measurement of I/Vρ			
V volume/cm^3	2.7552	–	0.09
I ionization current/pA		0.04	0.06
Overall Uncertainty			
Quadratic summation		0.07	0.27
Combined Uncertainty		0.28	

$^{a)}$ at 0 °C and 101.325 kPa (note that reference conditions are 22°C and the same pressure).

$^{b)}$ combined uncertainty on the product of $\left(\frac{\overline{L}}{\rho}\right)^{\text{graphite}}_{\text{air}} \left(\frac{W}{e}\right)_{\text{air}}$

$^{c)}$ ICRU Report 37 gives an uncertainty of 5% for the radiative stopping powers in this region and this uncertainty dominates the uncertainty in $\overline{g}$. ICRU Report 37 gives uncertainties at about the 90% confidence level and thus the one standard deviation uncertainty on $\overline{g}$ is taken as 3%. This in turn implies an absolute uncertainty on $\overline{g}$ of 0.0001 which transfers to the relative uncertainty on $1 - \overline{g}$ of 0.01%.

V COMPARISONS WITH OTHER PRIMARY STANDARDS

value plays a central role in international comparisons. In the most recent comparison with BIPM, the ratio of the NRC to the BIPM standard for ^{60}Co air kerma was 1.0020 and thus with the new NRC standard this value would be 1.0079. This large difference is expected and is consistent with preliminary results for the revised standards at other National Metrological Institutes.

VI Summary

Effective Oct 1, 2003, all NRC air-kerma calibration factors in a ^{60}Co beam will reflect the new value of the NRC standard. To convert old air-kerma calibration factors to be consistent with the new standard, one multiplies the old values by 1.0059. This means that all air-kerma or air-kerma rate determinations by the end user will increase by 0.59% for a given reading from an ion chamber. Similarly, all doses assigned using the old AAPM TG-21 protocol[28,29] will increase by 0.59%.

The current changes have no effect on the absorbed-dose standards at NRC and thus there is no change in absorbed-dose calibration factors. Doses determined using the AAPM TG-51 dosimetry protocol[30] are not affected. The effect of the change is to reduce the differences between doses assigned using TG–21 and TG–51 since TG–51 doses are all slightly higher than TG–21 doses.[31]

The changes reported here will also affect the NRC air-kerma calibrations in a ^{137}Cs beam since these are based on a transfer of the ^{60}Co standard to the ^{137}Cs beam.

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References

[1] D. W. O. Rogers, A. F. Bielajew, and A. E. Nahum, Ion chamber response and A_{wall} correction factors in a ^{60}Co beam by Monte Carlo simulation, Phys. Med. Biol. **30**, 429 – 443 (1985).

[2] D. W. O. Rogers and A. F. Bielajew, Wall attenuation and scatter corrections for ion chambers: measurements versus calculations, Phys. Med. Biol. **35**, 1065 – 1078 (1990).

[3] A. F. Bielajew, Correction factors for thick-walled ionisation chambers in point-source photon beams, Phys. Med. Biol. **35**, 501 – 516 (1990).

[4] A. F. Bielajew, On the technique of extrapolation to obtain wall correction factors for ion chambers irradiated by photon beams, Med. Phys. **17**, 583 – 587 (1990).

[5] A. F. Bielajew and D. W. O. Rogers, Implications of new correction factors on primary air kerma standards in ^{60}Co beams, Phys. Med. Biol. **37**, 1283 – 1291 (1992).

[6] D. W. O. Rogers and J. Treurniet, Monte Carlo calculated wall and axial non-uniformity corrections for primary standards of air kerma, NRC Report PIRS–663, NRC, Ottawa, 1999 (see http://www.irs.inms.nrc.ca/inms/irs/papers/PIRS663/pirs663.html).

[7] K. R. Shortt, A. F. Bielajew, C. K. Ross, K. J. Stewart, J. T. Burke, and M. J. Corsten, The effect of wall thickness on the response of a spherical ionization chamber, Phys. Med. Biol. **47**, 1721 – 1731 (2002).

[8] R. F. Laitano, M. P. Toni, M. Pimpinella, and M. Bovi, Determination of $\mathrm{K}_{\mathrm{wall}}$ correction factor for a cylindrical ionization chamber to measure air-kerma in ^{60}Co gamma beams, Phys. Med. Biol. **47**, 2411 – 2431 (2002).

[9] L. Büermann, H. M. Kramer, and I. Csete, Results supporting calculated wall correction factors for cavity chambers, Phys. Med. Biol. (in press, 2003).

[10] S. M. Seltzer and P. M. Bergstrom, Changes in the US Primary Standards for the Air Kerma from Gamma-Ray Beams, in press, J. Res. Natl. Inst. Stand. Technol. (2003).

[11] Changes in the Canadian Primary Standards for Exposure and Air Kerma and the Associated Calibration Factors, Flyer from Ionizing Radiation Standards Group, NRC, Ottawa (1990).

[12] J. Borg, I. Kawrakow, D. W. O. Rogers, and J. P. Seuntjens, Monte Carlo study of correction factors for Spencer-Attix cavity theory at photon energies at or above 100 keV, Med. Phys. **27**, 1804 – 1813 (2000).

[13] D. W. O. Rogers and I. Kawrakow, Monte Carlo calculated correction factors for primary standards of air-kerma, Med. Phys. **30**, 521 – 543 (2003).

[14] K. R. Shortt and C. K. Ross, The Canadian ^{60}Co Exposure Standard, National Research Council of Canada Report PIRS-0052 (1986).

[15] D. W. O. Rogers, Fundamentals of High Energy X-ray and Electron Dosimetry Protocols, in *Advances in Radiation Oncology Physics, Medical Physics Monograph 19*, edited by J. Purdy, pages 181 – 223, AAPM, New York, 1992.

[16] D. W. O. Rogers and C. K. Ross, The Role of Humidity and Other Correction Factors in the AAPM TG–21 Dosimetry Protocol, Medical Physics **15**, 40 – 48 (1988).

[17] G. Mora, A. Maio, and D. W. O. Rogers, Monte Carlo simulation of a typical ^{60}Co therapy source, Med. Phys. **26**, 2494 – 2502 (1999).

[18] N. Takata, T. Kurosawa, and Y. Koyama, Ionization chamber wall correction factors and angular dependences of responses in measuring air kerma for gamma rays, BIPM Report CCRI(I)/03 – 18 , 4 pages (2003).

[19] N. Takata, T. Kurosawa, and N. T. Tran, Angular dependence of signal currents from cylindrical ionization chambers, Radiat. Prot. Dosim. (in press, 2003).

[20] P. J. Allisy-Roberts, D. T. Burns, K. R. Shortt, and C. K. Ross, Comparison of the air kerma standards of the NRC and the BIPM for ^{60}Co γ rays, Rapport BIPM-99/12 (2000).

[21] ICRU, Stopping powers for electrons and positrons, ICRU Report 37, ICRU, Washington D.C., 1984.

[22] M. S. MacPherson, C. K. Ross, and D. W. O. Rogers, Measured electron stopping powers for elemental absorbers, Med. Phys. (abs) **23**, 797 (1996).

[23] M. S. MacPherson, PhD Thesis: Accurate Measurements of the Collision Stopping Powers for 5 to 30 MeV Electrons, NRC Report PIRS 626 (1998).

[24] K. Shortt, J. Shobe, and S. Domen, Comparison of Dosimetry Calibration factors at the NRCC and the NIST, Med. Phys. **27**, 1644 – 1654 (2000).

[25] K. R. Shortt, C. K. Ross, M. Schneider, K. Hohlfeld, M. Roos, and A.-M. Perroche, A Comparison of Absorbed Dose Standards for High Energy X-rays, Phys. Med. Biol. **38**, 1937 – 1955 (1993).

[26] K. R. Shortt, C. K. Ross, J. P. Seuntjens, F. Delaunay, A. Ostrowsky, P. Gross, and E. Leroy, Comparison of dosimetric standards of Canada and France for Photons at ^{60}Co and higher energies, Phys. Med. Biol. **46**, 2119 – 2142 (2001).

[27] K. R. Shortt, R. B. Huntley, L. H. Kotler, and J. F. Boas, A comparison of the Australian and Canadian standards of air kerma and absorbed dose to water for ^{60}Co γ radiation, in preparation (2003).

[28] AAPM TG–21, A protocol for the determination of absorbed dose from high-energy photon and electron beams, Med. Phys. **10**, 741 – 771 (1983).

[29] R. J. Schulz, P. R. Almond, G. Kutcher, R. Loevinger, R. Nath, D. W. O. Rogers, N. Suntharalingham, K. A. Wright, and F. Khan, Clarification of the AAPM Task Group 21 Protocol, Medical Physics **13**, 755 – 759 (1986).

[30] P. R. Almond, P. J. Biggs, B. M. Coursey, W. F. Hanson, M. S. Huq, R. Nath, and D. W. O. Rogers, AAPM's TG–51 Protocol for Clinical Reference Dosimetry of High-Energy Photon and Electron Beams, Med. Phys. **26**, 1847 – 1870 (1999).

[31] D. W. O. Rogers, Why To Use TG–51, Interactions (COMP Newsletter) **46,#3**, 106 – 107 (2000).