Implications of new correction factors on primary air kerma standards in ^{60}Co-beams

1992 Phys. Med. Biol. 37 1283

(http://iopscience.iop.org/0031-9155/37/6/006)

Phys. Med. Biol., 1992, Vol. 37, No 6, 1283–1291. Printed in the UK

Implications of new correction factors on primary air kerma standards in ^{60}Co-beams

A F Bielajew and D W O Rogers
Institute for National Measurement Standards, National Research Council of Canada, Ottawa, Canada K1A 0R6

Received 9 October 1991

Abstract. Comparisons of primary standards for air kerma in ^{60}Co-beams are re-analysed taking into account the recently developed formalism that defines uniquely the various correction factors and the development of analytic and Monte Carlo methods to quantify these corrections. After a brief historical review of air kerma comparisons and ion chamber calculations, the new corrections are applied in a re-analysis of previously published comparison data. An independent Monte Carlo verification of the analytic point-source non-uniformity correction factor is presented. The combination of new proposed correction factors imply that some national standards should increase by as much as 1% and that the global increase is of the order of 0.6%.

1. Introduction

Comparisons form the basis of verification for national primary standards of air kerma†. The following lists direct comparisons where national primary standards for ^{60}Co-beams have been compared in the same beam with the standard of the Bureau International des Poids et Mesures, France (BIPM): (i) 1975 Physikalisch-Technische Bundesanstalt, Federal Republic of Germany (PTB) (Niatel *et al* 1975), (ii) 1975 National Institute for Standards and Technology, USA, formerly NBS (National Bureau of Standards) (NIST) (Niatel *et al* 1975), (iii) 1983 Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative, Italy (ENEA) (Laitano and Toni 1983), (iv) 1986 Instituto de Radioproteçao e Dosimetria, Brazil (IRD) (de Almeida and Niatel 1986).

The following lists indirect comparisons in which transfer chambers were compared at the BIPM and a second measurement made in the home laboratory of the other country: 1974, 1992 National Research Council Canada (NRCC) (Niatel 1975, Shortt *et al* 1992). While this list is not exhaustive, it represents a compilation of all the published and unpublished data that were made available to us.

Each standard requires adjustment for various effects. The adjustments or corrections of interest in this paper are associated with photon attenuation and scatter in the walls of the chamber, electron drift in the chamber walls, and effects of changes in the incident photon field over the extent of the chamber. There are many other corrections, some of which cancel when the comparison is made. Every national laboratory has its own correction factors and means of determining them, often an

† In this report, the changes reported also apply directly to exposure.

0031-9155/92/061283+09$04.50

ad hoc combination of theoretical calculations and experimental data. However, a general formalism for characterizing thick-walled ion chamber response in uniform photon beams has been established (Bielajew 1986). This work puts the Monte Carlo calculation of correction factors on a solid theoretical footing. The formalism was recently extended to point-source beams (Bielajew 1990a). Furthermore, an analytic theory was developed that allowed calculation of corrections for point-source effects at typical measurement distances (Bielajew 1990b), since the Monte Carlo calculations of these corrections is (currently) prohibitively expensive in terms of computer processing time. This analytic development was based upon an extension of Kondo and Randolph's theory (Kondo and Randolph 1960) and was supported by independent Monte Carlo calculations. Its results were about 0.5% different from the one-dimensional analytic approach of Boutillon and Niatel (1973).

There have been parallel developments concerning the calculation of wall correction factors. Using the Monte Carlo technique, Nath and Schulz (1981) calculated ion chamber response and correction factors associated with photon attenuation and scatter, and with electron drift. While their calculations of chamber response drew much criticism (Nahum and Kristensen 1982, McEwan and Smyth 1984, Bielajew *et al* 1985, Rogers *et al* 1985), their calculated correction factors have been improved only slightly by subsequent calculations (McEwan and Smyth 1984, Rogers *et al* 1985, Rogers and Bielajew 1990).

However, in this last paper it was shown that Monte Carlo-calculated wall correction factors differed by up to 1% from the measured correction factors, which were mostly based on an extrapolation of chamber response versus wall thickness data and a value of K_{cep}, the correction for electron drift. This paper also demonstrated that the same Monte Carlo code could reproduce the response versus wall thickness data to within an accuracy of $\pm 0.05\%$. For spherical chambers, Bielajew (1990c) devised a simple analytic explanation that casts doubt upon experimental determinations of wall correction factors by linear extrapolation of the response data. In view of these new insights into the behaviour of ion chambers, the good agreement between the Monte Carlo calculations and the response data for chambers of various shapes and the theoretical demonstration of the failure of the linear extrapolation techniques for spherical chambers, it is preferable to use the Monte Carlo-calculated values of K_{wall} rather than extrapolate the experimental data.

The Canadian primary standard for air kerma in a ^{60}Co beam has been revised to reflect the values obtained from these theories and Monte Carlo calculations (effective July 1990). The present work offers a summary of the effects of similar changes on other national primary standards and the comparisons which have been reported. It will be shown that, despite some rather large individual changes and an overall increase in the air-kerma scale of about 0.6%, the consistency between primary standards remains very good.

2. Notation

The scope of this report is limited to two correction factors. K_{wall} corrects for attenuation, scatter and electron drift in the chambers walls. It is a composite factor but it is a natural output from Monte Carlo codes (Bielajew 1986). It replaces or encompasses other factors known as K_{at} (γ-attenuation, BIPM), K_{sc} (γ-scatter, BIPM), K_{cep} (e$^-$-drift, NIST), K'_{cep} (e$^-$-drift, PTB), K'_{cep} (e$^-$-drift, BIPM), K_c

(γ-attenuation and γ-scatter, NIST, PTB), and K_w (γ-attenuation, γ-scatter, and e^--drift), as discussed in Niatel *et al* (1975). For example, K_{wall} replaces the product $K_{at}K'_{cep}K_{sc}$ for the BIPM standard, $K_c K_{cep}$ for the NIST standards, and $K_c K'_{cep}$ for the PTB standards.

K_{pn}, the point-source non-uniformity correction factor (Bielajew 1990a), accounts for the finite size of the chamber in the diverging r^{-2} field of the source. This factor accounts not only for the r^{-2} fall-off but also for the skewness of the electron trajectories produced by the diverging field. This leads to a cavity-geometry dependency that can be surprisingly large for some chambers (Bielajew 1990b). To account for departures from r^{-2} fall-off and point-source characterization, it is necessary to introduce a new correction factor, K_{npn} (non-point-source non-uniformity). This would account for the effects of collimator scatter and the finite size of the source capsule. The product $K_{pn}K_{npn}$ replaces the product $K_{an}K_{rn}$ used in most current analyses. K_{an} accounts for field non-uniformity in the direction from the source to the chamber ('axial non-uniformity') and K_{rn} for non-uniformity in the perpendicular direction ('radial non-uniformity'). By definition, K_{pn} accounts for all non-uniformities arising from the presence of a point-source field and thus assumes the point-source part of the non-uniformity associated with K_{rn}.

Measurements of K_{rn} have been carried out by Boutillon and Niatel (1973) and Loftus and Weaver (1974). Boutillon and Niatel infer that for the BIPM's plane-parallel chamber K_{rn} has the value of 1.0013 ± 0.0005 at the BIPM's standard measurement distance of 1.12 m. A simple analysis reveals that this correction includes only a 0.02% contribution from the r^{-2} nature of the source and therefore most of the correction must be from other effects. Loftus and Weaver inferred that the K_{rn} correction at their standard measurement distance of 2 m was less than 0.02 %. Thus in the following analysis, K_{rn} is associated with K_{npn} and assumed not to change, and K_{an} is replaced by K_{pn}. This represents a slight change from the procedure suggested in Bielajew (1990b).

3. Comparison of National Standards

3.1. Physical data

The physical data associated with the chambers considered in this report are summarized in table 1. They were taken from Boutillon and Niatel (1973), Loftus and Weaver (1974), Laitano and Toni (1983), de Almeida and Niatel (1986), Shortt and Ross (1986) and Engelke *et al* (1988).

3.2. New correction factors

The new correction factors are compiled in table 2. The uncertainties quoted in this table and throughout this report follow the Comité International des Poids at Mesures (CIPM) conventions (1981). Where relevant, the type A or B (1σ) uncertainties are given explicitly. The notation 1.0037(12) should be interpreted as $1.0037(12) = 1.0037 \pm 0.0012(1\sigma)$, where the type A and B uncertainties have been added in quadrature. The original publications were not always clear about the confidence level assigned to various quantities, and in many cases more recent reports allow more accurate values to be given. We have chosen to use the original numbers

Table 1. Physical dimensions for the graphite ion chambers examined in this study.

Laboratory	Shape	ρ (g cm^{-3})	Inner radius (cm)	Outer radius (cm)	Radial wall thickness (cm)	Inner length (cm)	Outer length (cm)	Planar wall thickness (cm)	Electrode diameter/length (cm)
BIPM	double ‖-plane	1.84	2.250	2.525	0.275	0.513	1.079	0.283	4.098/0.102
NIST	1 cm^3 sphere	1.73	0.635	1.033	0.398				0.1/1†
	10 cm^3 sphere	1.72	1.339	1.714	0.3755				0.1/2
	30 cm^3 sphere	1.74	1.928	2.304	0.3751				0.1/3
	50 cm^3 sphere	1.73	2.30	2.67	0.3652				0.3/4
	50 cm^3 sphere	1.73	2.28	2.79	0.5085				0.3/4
	50 cm^3 sphere	1.73	2.29	2.90	0.6129				0.3/4
NRCC	cylinder	1.66	0.7919	1.175	0.383	1.6135	2.526	0.456	0.6704/1.2002
PTB(a)	cylinder	1.73	0.3	0.6	0.300	2.0	2.7	0.35	0.12/1.75
PTB(b)	cylinder	1.73	0.5	0.8	0.300	2.0	2.7	0.35	0.20/1.60
PTB(c)	double ‖-plane	1.73	2.2	2.6	0.398	0.45	1.25	0.40	4.00/0.05
ENEA	cylinder	1.75	0.55	0.95	0.4	1.1	1.9	0.4	0.2/1.
IRD	cylinder	1.71	0.55	0.95	0.4	1.1	1.9	0.4	0.2/1.

† The dimensions of the NIST electrodes were estimated from volume measurements.

Table 2. Summary of proposed new correction factors. The numbers in parentheses represent 1σ estimates of the uncertainty in the last digits. For the new K_{wall} correction factors, only the type B uncertainty from the Monte Carlo calculations are given.

Lab.	Shape	K_{wall}^{old}	K_{wall}^{new}	Δ	K_{an}	K_{pn}	Δ	$\Sigma\Delta$
BIPM[a]	double ‖-plane	1.0037(12)	1.0008(6)	−0.29%	0.9968(10)	1.0022	+0.54%	+0.25%
NIST[b]	1 cm^3 sphere	1.0117(18)	1.0207(8)	+0.89%	1.0000(5)	1.0000	0.00%	+0.89%
	10 cm^3 sphere	1.0165(11)	1.0247(6)	+0.81%	1.0000(5)	1.0001	+0.01%	+0.82%
	30 cm^3 sphere	1.0169(11)	1.0263(6)	+0.92%	1.0000(5)	1.0001	+0.01%	+0.93%
	50 cm^3 sphere	1.0176(11)	1.0261(6)	+0.84%	1.0000(5)	1.0002	+0.02%	+0.86%
	50 cm^3 sphere	1.0267(11)	1.0367(6)	+0.97%	1.0000(5)	1.0002	+0.02%	+0.99%
	50 cm^3 sphere	1.0335(11)	1.0432(7)	+0.94%	1.0000(5)	1.0002	+0.02%	+0.96%
NRCC[c]	cylinder	1.0198(22)	1.0218(5)	+0.20%	1.0000(20)	1.0001	+0.01%	+0.21%
PTB(a)[d]	cylinder	1.0092(8)	1.0086(4)	−0.06%	0.9955(8)	1.0005	+0.50%	+0.44%
PTB(b)	cylinder	1.0097(9)	1.0113(3)	+0.16%	0.9925(8)	1.0005	+0.81%	+0.97%
PTB(c)	double ‖-plane	1.0068(13)	1.0014(7)	−0.54%	0.9933(8)	1.0030	+0.98%	+0.43%
ENEA[e]	cylinder	1.0128(11)	1.0197(5)	+0.68%	0.9970(5)	1.0001	+0.31%	+0.99%
IRD[f]	cylinder	1.0125(8)	1.0200(9)	+0.74%	1.0000(7)	1.0001	+0.01%	+0.75%

[a] Niatel *et al* (1974) quote uncertainties as 'upper limits' which are we have interpreted as 95% confidence limits (2σ) and modified for use in this table. However, the data in de Almeida and Niatel (1986) suggest that the 1σ limits are 0.07% and 0.08% for K_{wall} and K_{an}, respectively.
[b] The NBS uncertainties on K_{wall} come from Loftus and Weaver (1974) who clearly state they are 2σ uncertainties. However they quote no uncertainty on K_{an}. In Niatel *et al* an uncertainty of 0.1% is assigned to this factor which we have interpreted as a 2σ uncertainty.
[c] From Shortt and Ross (1986).
[d] These values are from Niatel *et al* (1974) where the uncertainties are presented as 'upper limits'. However, in Engelke *et al* (1988) it is clear that these uncertainties were only 1σ. Note also that the newer paper would reduce all K_{wall} values by 0.3% because of a change in K_{cep} from 0.997 to 0.994. This would increase the size of the change implied by the Monte Carlo calculations. Also, the values given in Niatel *et al* for the factor K_{an} at 112 cm correspond to the values in Engelke *et al* for 100 cm. The values at 112 cm would be 0.05 to 0.08% larger.
[e] From Laitano and Toni (1983).
[f] From de Almeida and Niatel (1986).

in most cases but have reported them all as 1σ uncertainties and given footnotes concerning more recent results.

Type A uncertainties are not included in table 2 for the new values of K_{wall} or K_{pn}. In a previous report a type A uncertainty of 0.10% was ascribed to K_{pn} (Bielajew 1990b). In this report we have reduced this to 0.05% because the values presented here include an estimate of electrode effects for the plane-parallel chambers and because the analytic values have been confirmed by Monte Carlo calculations (see below). The factors K_{wall} have been found to reproduce experimental data at the ±0.05% level (Rogers and Bielajew 1990). Thus a type A uncertainty of 0.05% is assigned to K_{wall}.

The values of K_{pn} are for a distance from the point source to the cavity centre of 1.12 m. Values for other distances may be obtained from a previous report (Bielajew 1990b). The new values of K_{wall} are based on Monte Carlo calculations which explicitly account for all the dimensional data presented in table 1 (Rogers and Bielajew 1990). The only difference was that the electrodes in the five largest NIST chambers were not modelled, but even much larger electrodes have been found to have very little, if any, effect in all other chamber calculations.

3.3. Independent Monte Carlo verification of K_{pn}

The point-source non-uniformity correction factors K_{pn}, listed in table 2, are based on analytic calculations that make the assumptions that the electron distributions are nearly semi-isotropic $(1+1.1\cos\Theta)$ and that the cavity shapes are pure right cylinders or perfect spheres with no electrode. To test these approximations, direct Monte Carlo evaluations of K_{pn} were performed for two chambers: the BIPM chamber (similar in geometry to the PTB plane-parallel chamber), and the NRCC chamber (a representative cylindrical chamber). Simulations were performed both with and without electrodes with a realistic ^{60}Co source. The simulations are similar to those described elsewhere (Bielajew 1990a), except for some important distinctions. The value of K_{pn} was taken as a correlated ratio of the chamber response per unit primary, unattenuated photon fluence in a broad parallel beam to that with a point source. (This is the inverse of equation (16) of Bielajew (1990a).) No point-source 'unweighting' technique was applied and the cavity gas was assumed to be air at 20 °C and 1 atmosphere.

The correlation technique, which involved restarting each history with the same random-number state in both the point-source and parallel-beam configurations, saved a factor of two to four in computing time. Nonetheless, the computations used copious computing resources and the computing time in equivalent VUP's (Vax 11/780 FPA unit of power) is tabulated with the results in table 3.

Table 3. Monte Carlo tests of K_{pn} compared with analytic theory. The uncertainties quoted are 1σ estimates and are type A for the analytic theory and type B for the Monte Carlo calculations.

Chamber	Electrode	K_{pn}^{theory}	$K_{pn}^{Monte\ Carlo}$	CPU days
BIPM	no	1.0031(5)	1.0030(6)	59
BIPM	yes	1.0022(5)	1.0021(6)	47
NRCC	no	1.0001(5)		
NRCC	yes		0.9999(6)	126

The lengthy Monte Carlo calculations verify the analytic calculations. In the case of the BIPM chamber, the analytic method was extended trivially to allow for the electrode by making the assumption that the electrode and cavity radius are the same (rendering the cavity into two separate adjacent cavities). One notes that the 0.09% decrease, predicted by the analytic method for the double cavity, is suggested (perhaps fortuitously) by the Monte Carlo calculation. In the case of the NRCC chamber, the presence of the electrode did not make a difference, leaving the result very close to unity.

These results support strongly the analytic method proposed by Bielajew (1990b). Further simulations were not attempted following consideration of these results.

3.4. Revised comparison

The proposed changes implied by the new correction factors are summarized in table 4 and figure 1. The values of the ratios presented there have effects associated with the use of different stopping-power ratios eliminated. The uncertainties in column 3 were obtained from those in column 2 by replacing the original estimates of the 1σ uncertainties in K_{an} and K_{wall} by the uncertainties in the present calculations, as given in table 2 for type B uncertainties plus 0.05% type A uncertainties in each. Table 4 shows that the standard deviation in the sample and the spread in the data remain roughly the same.

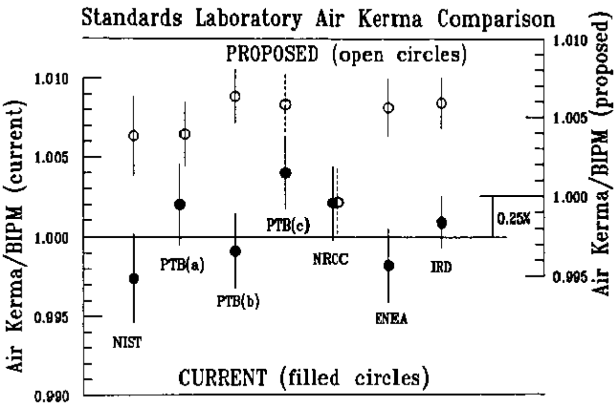

Figure 1. Current and proposed air kerma comparison data proposed in this report. The proposed data are referred to the right axis which is offset by the 0.25% increase proposed for the BIPM standard.

The uncertainties in K_{wall}, K_{an}, and K_{rn} usually dominate the uncertainty of the comparison. There are also small contributions to the uncertainty from charge measurement, saturation corrections, volume measurements and stem corrections. Individually, these corrections are of the order of 0.05% or less and contribute very little when summed in quadrature with the dominant factors. In the NIST case, originally a further correction was employed to renormalize the chamber employed (the NIST 1 cm^3 chamber) to the weighted mean of all six NIST chambers, but this was not taken into account in determining the revised ratio.

As seen in table 2, in most cases the Monte Carlo-calculated wall correction factors are quoted with smaller type B uncertainties (to which the 0.05% type A uncertainty must be added) than their experimentally determined counterparts. This is the principle cause for the reduction in uncertainties in the re-analysed comparison data.

4. Discussion and Conclusions

It has been shown that by using a consistent and theoretically justified approach to obtaining the K_{pn} and K_{wall} correction factors for primary standards of air kerma, the overall consistency of several primary standards is maintained, despite the rather large changes which are required. Since (i) these techniques have been derived in a consistent manner based on a solid theoretical footing, (ii) the Monte Carlo codes involved have been carefully tested against a variety of experimental data, and (iii) it has been demonstrated that the linear extrapolation technique does not always work; it is suggested that the new approach to correction factors summarized in this report deserves serious consideration for implementation in national primary standards of air kerma in a ^{60}Co beam. If this were done, the global air kerma scale would increase by

Table 4. Revised air kerma comparison data using K_{pn} and K_{wall} correction factors proposed in this report. The uncertainties are 1σ estimates of the uncertainty in the comparison.

Laboratory	$\left(\frac{K_{air}}{K_{air}^{BIPM}}\right)^{a}_{current}$	$\left(\frac{K_{air}}{K_{air}^{BIPM}}\right)^{b}_{proposed}$
NIST	0.9974 ± 0.28%	1.0038[c] ± 0.25%
NRCC[d]	1.0021 ± 0.23%	0.9996 ± 0.21%
PTB(a)[e]	1.0020 ± 0.25%	1.0039 ± 0.20%
PTB(b)	0.9991 ± 0.23%	1.0063 ± 0.17%
PTB(c)	1.0040 ± 0.23%	1.0058 ± 0.19%
ENEA[f]	0.9982 ± 0.23%	1.0056 ± 0.18%
IRD	1.0009 ± 0.16%	1.0059 ± 0.16%
Average[g]	1.0005	1.0039[h]
Sample std. dev.	0.22	0.27
Spread	0.66%	0.67%

[a] These ratios are the same as would be expressed for the exposure rate, $\dot{X}$.

[b] The proposed ratios include the 0.25% increase of the BIPM standard.

[c] This number treats the change as if it came solely from the 1 cm^3 chamber, whereas the comparison also included a complex averaging technique. This approximation should not affect the result by more than 0.1%.

[d] The current value is that reported in Shortt *et al* (1992), which already includes the proposed changes for the NRCC standard.

[e] As discussed in the footnotes to table 2, the uncertainties in the original PTB data taken from Niatel *et al* (1974) should be revised to 0.31%, 0.29% and 0.29%, and the current ratios reduced by about 0.25%, 0.21% and 0.22%. These changes would not affect the proposed ratios.

[f] Uncertainty deduced using the method in Niatel *et al* (1974) and data in Laitano and Toni (1983).

[g] The average includes a value of unity for the BIPM chamber.

[h] The overall shift is 0.39% + 0.25% = 0.6%, but the exact value depends on how various chambers are included in the average.

about 0.6%. Any change based on theoretical considerations ought to be verified by further experiment followed by an all-inclusive set of calculations, encompassing the air kerma standards of all primary laboratories. Our computer codes for calculating the correction factors are available to any national dosimetry standards' laboratory.

Résumé

Implications des nouveaux facteurs de correction pour les références primaires du kerma dans l'airs dans les faisceaux de photons du ^{60}Co.

Les auteurs ont repris une analyse des comparaisons des références primaires pour le kerma dans l'air dans les faisceaux de photons du ^{60}Co, en tenant compte de la formulation développée récemment, et qui précise d'une manière unique les divers facteurs de correction, et de la mise au point de méthodes analytiques et de Monte Carlo pour quantifier ces corrections. Après une brève revue historique des comparaisons de kerma dans l'airs, et des calculs effectués à partir de chambres d'ionisation, les auteurs appliquent les nouvelles corrections dans une nouvelle analyse des données utilisées pour la comparaison, publiées antérieurement. Ils présentent une vérification indépendante, á l'aide de la méthode. Monte Carlo, du facteur de correction analytique de la non uniformité d'une source ponctuelle. La combinaisondes nouveaux facteurs de correction proposés implique que quelques références nationales soient augmentées d'une quantité allant jusqu'à 1%, et que l'augmentation globale soit de l'ordre de 0.6%.

Zusammenfassung

Die Bedeutung neuer Korrekturfaktoren für die primären Luft-Kerma-Standards in ^{60}Co-Strahlen.

Vergleiche der primären Standards für die Luft-Kerma-Standards in ^{60}Co-Strahlen wurden reanalysiert unter Berücksichtigung des kürzlich entwickelten Formalismus, der die verschiedenen Korrekturfaktoren einheitlich formuliert, sowie unter Berücksichtigung der Entwicklung analytischer und Monte Carlo-Methoden zur Quantifizierung dieser Korrekturfaktoren. Nach einem kurzen historischen Überblick über die Luft-Kerma-Vergleiche und die Ionisationskammerberechnungen werden die neuen Korrekturen angewandt bei einer Reanalyse früher veröffentlicher Vergleichsdaten. Eine unabhängige Monte Carlo-Verifizierung des analytischen Inhomogenitätskorrekturfaktors für Punktquellen wird vorgestellt. Die Kombination neu vorgeschlagener Korrekturfaktoren hat zur Folge, daß die Erhöhung global betrachtet bei etwa 0.6% liegt.

References

de Almeida C E and Niatel M-T 1986 Comparison between IRD and BIPM exposure and air-kerma standards *BIPM Report* BIPM-86/12 (Sèvres: BIPM)

Bielajew A F 1986 Ionization cavity theory: a formal derivation of perturbation factors for thick-walled ion chambers in photon beams *Phys. Med. Biol.* **31** 161–70

Bielajew A F 1990a Correction factors for thick-walled ionisation chambers in point-source photon beams *Phys. Med. Biol.* **35** 501–16

Bielajew A F 1990b An analytic theory of the point-source non-uniformity correction factor for thick-walled ionisation chambers in photon beams *Phys. Med. Biol.* **35** 517–38

Bielajew A F 1990c On the technique of extrapolation to obtain wall correction factors for ion chambers irradiated by photon beams *Med. Phys.* **17** 583–7

Bielajew A F, Rogers D W O and Nahum A E 1985 The Monte Carlo simulation of ion chamber response to ^{60}Co—resolution of anomalies associated with interfaces *Phys. Med. Biol.* **30** 419–27

Boutillon M and Niatel M-T 1973 A study of a graphite chamber for absolute exposure measurements of ^{60}Co gamma rays *Metrologia* **9** 139–46

Comité International des Poids at Mesures 1981 *Procès-Verbaux (CIPM Report)* **49**

Engelke B-A, Oetzmann W and Struppek G 1988 Die Meßeinrichtungen der Physikalisch-Technische Bundesanstalt zur Darstellung der Einheiten der Standard-Ionendosis, Photonen-Äquivalentdosis und Luftkerma *PTB Report* PTB-Dos-16 (Braunschweig: PTB)

Kondo S and Randolph M L 1960 Effect of finite size of ionization chambers on measurements of small photon sources *Radiat. Res.* **13** 37–60

Laitano R F and Toni M P 1983 The primary exposure standard for Co-60 gamma radiation: characteristics and measurement procedures *ENEA Report* RT/PROT(83)28 (Casaccia, Rome: ENEA)

Loftus T P and Weaver J T 1974 Standardization of ^{60}Co and ^{137}Cs gamma-ray beams in terms of exposure *J. Res. NBS* **78A** 465–76

McEwan A C and Smyth V G 1984 Comments on Calculated response and wall correction factors for ionization chambers exposed to ^{60}Co gamma-rays *Med. Phys.* **11** 216–8

Nahum A E and Kristensen M 1982 Calculated response and wall correction factors for ionization chambers exposed to ^{60}Co gamma-rays *Med. Phys.* **9** 925–7

Nath R and Schulz R J 1981 Calculated response and wall correction factors for ionization chambers exposed to ^{60}Co gamma-rays *Med. Phys.* **8** 85–93

Niatel M-T 1975 Exposure Standard comparisons *BIPM report* CCEMRI(I)/75-13

Niatel M-T, Loftus T P and Oetzmann W 1975 Comparison of exposure standards for ^{60}Co gamma rays *Metrologia* **11** 17–23

Rogers D W O and Bielajew A F 1990 Wall attenuation and scatter corrections for ion chambers: measurements versus calculations *Phys. Med. Biol.* **35** 1065–78

Rogers D W O, Bielajew A F and Nahum A E 1985 Ion chamber response and A_{wall} correction factors in a ^{60}Co beam by Monte Carlo simulation *Phys. Med. Biol.* **30** 429–43

Shortt K R and Ross C K 1986 The Canadian ^{60}Co exposure standard *NRCC Report* PIRS-0052 (Ottawa: NRCC)

Shortt K R, Ross C K, Schneider M, Hohlfeld K, Roos M and Perroche A-M 1992 A Comparison of absorbed dose standards for high energy x-rays, in preparation