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Changes to the NPL air kerma standard for ^{137}Cs and ^{60}Co

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Department for **Innovation, Universities** & **Skills**

Changes to the NPL air kerma standard for ^{137}Cs and ^{60}Co

by

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ABSTRACT

The NPL maintains a primary standard of air kerma defined as the mean corrected response of three cavity ionisation chambers, which were designed to operate in 2 MV X-rays at therapy-level air kerma rates. The therapy level exposure calibration service for 2 MV X-rays was first instituted at the NPL in 1956; a chamber correction factor F was applied to the mean response of the standard cavity chambers. This factor was revised in 1969 and again in 1992 for 1 MV and 2 MV X-rays and for ^{137}Cs and ^{60}Co γ-rays. This report documents the changes to the correction factors and presents new work re-evaluating the chamber correction factors for ^{137}Cs and ^{60}Co γ-rays. Adoption of the new correction factors from 1st May 2009 will result in an increase of the NPL air kerma standard by ~1% for both therapy and protection levels.

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CONTENTS

TABLES

1 BACKGROUND

1.1 1956 - 1969

The NPL maintains a primary standard of air kerma defined as the mean corrected response of three cavity ionisation chambers, which were designed to operate in 2 MV X-rays at therapy-level air kerma rates. When the therapy level exposure calibration service for 2 MV X-rays was first instituted at the NPL in 1956, a chamber correction factor F of 1.03 ± 0.01 was applied to the mean response of the standard cavity chambers.

1.2 1969 - 1992

Later, analysis by Barnard et al [1,2] led to the following expression for the chamber correction factor F:

$$F = {}_m\bar{S}_{air}^{C} \left(\bar{\mu}_{en}/\rho\right)_C^{air} \cdot f_{wall} \cdot f_{el.equil.} \cdot f \qquad (1)$$

where:

$\left(\bar{\mu}_{en}/\rho\right)_C^{air}$ is the mean mass energy absorption coefficient ratio;

${}_m\bar{S}_{air}^{C}$ is the mean mass stopping power ratio;

f_{wall} is the wall correction factor that accounts for the decrease in the chamber response caused by attenuation of the incident photon beam in the walls and for the increase caused by photon scatter in the walls;

$f_{el.equil.}$ is a correction to account for the lack of electronic equilibrium in the chamber cavity;

f is a small composite correction that accounts for configuration factors (f_{conf} [i]), lack of saturation (f_{sat}) and polarity effects (f_{pol}) that occur during ionisation current measurements and for stem scatter effects (f_{ss}).

In this original work, values for all these factors were determined for the NPL primary standard chamber SCB1 under different conditions. The same factors were then applied to standard chambers SCA2 and SCA3: the primary standard being the mean of the three chambers. Table 1 gives values for these correction factors in both 1 MV and 2 MV X-rays that were adopted in 1969. The wall correction was based on a semi-empirical model, which did not involve an extrapolation to zero wall thickness, but which was supported by much measured data on chamber response as a function of wall material and thickness. The correction for stem scatter effects (f_{ss}) is based on measurements in a 2 MV X-ray beam and so the energy dependence of this factor was neglected at the time. The inclusion of the correction factor $f_{el.equil.}$ allows for

[i] It is a drawback of the design of these chambers that the electric field tends to zero in the upper corners of the air cavity. In this small volume ion recombination is never small and an additional correction has been applied.

incomplete build up in the highest energy beam. The chamber correction factors that were adopted for the protection–level calibration service for ^{137}Cs and ^{60}Co γ-rays were taken to be the same as those used for 1 MV and 2 MV X-rays respectively and so are not given in the table.

1.3 1992 - 2009

In 1985, Section I (Rayons X et γ, electrons) of the Consultative Committee on Standards for the Measurement of Ionising Radiations, CCEMRI(I), recommended at its 8th meeting that new values for a number of physical constants should be incorporated into the existing radiation measurement standards, from 1st January 1986. The report [3] recommended the use of new values for the following quantities: mass-stopping powers for electrons [4]; photon mass-energy absorption coefficients [5]; mean energy to create an ion-pair in air [6] and average fraction of the secondary electron energy that is lost to radiative interactions in air [7]. In the model used previously to determine the wall correction the dependence on electron mass-stopping power and photon mass-energy absorption data was not completely explicit: this made it difficult to incorporate revised values for electron and photon interaction data. Consequently the correction factor F was revised in 1992 based on the new recommended data and was determined using EGS4/PRESTA [8,9] Monte Carlo simulations.

These calculations were divided into two parts. Firstly the photon fluence spectra were determined for the X-ray and γ-ray facilities used in the calibration service under normal calibration conditions. These spectra were then used to calculate the chamber correction factor for each primary standard chamber. The correction factor $\widetilde{F}$ was obtained directly as a ratio of two Monte Carlo calculations of dose to the air cavity: one a realistic chamber and the other an idealised chamber with dense air walls which neither attenuate nor scatter. This method did not involve explicitly taking the product of the effective values for stopping power ratio, mass energy absorption coefficient ratio, wall correction and fluence perturbation correction. The overall ratio was obtained for each of the three NPL chambers, and a volume-weighted average taken. As a check on this overall result, separate calculations were made in 2 MV X-rays (for all three chambers) and ^{60}Co γ-rays (for one chamber SCB1) and values were obtained for the components separately and a comparison made with the overall ratio. A small discrepancy was found between these two routes that is accounted for by the correction factor f_{other}. As the correction for stem scatter effects (f_{ss}) is energy-dependent this correction was calculated using Monte Carlo techniques for each radiation quality for chamber SCB1 only. The corrections for configuration, saturation and polarity effects are assumed to be energy independent and so the values for these were retained.

Since 1996, following the demise of the NPL Van de Graaff, this standard has been used in therapy level ^{60}Co γ-rays either from a Mobaltron unit (1996-2000) or from a Theratron 780C (2000 to date). The Mobaltron and Mainance beams differ in the proportion of scattered radiation and also in diameter. Nevertheless therapy-level secondary standard calibrations in 2 MV X-rays and in the Mobaltron were found to be consistent at the 0.1% level provided the Mainance beam primary standard corrections were used for calibrations in the Mobaltron beam. It was decided not to attempt a full re-evaluation of the chamber corrections until the improved electron transport algorithms then in development were available in general purpose Monte Carlo codes. This re-evaluation has now been completed using the EGS4/BEAM [8, 10] and EGSnrc [11, 12] Monte Carlo systems, as described below. Adoption of the new correction factors will result in an increase of the NPL air kerma standard by 1% for both therapy and protection levels.

2 DEFINITION OF THE CAVITY CHAMBER CORRECTION

A description of the re-evaluation of the air kerma primary standard chamber correction factor now follows.

Air kerma, K_a, is determined from a measurement of the ionisation in a cavity chamber. Various effects prevent us from identifying the charge produced by ionisation in the cavity, Q, with the charge actually collected Q_{meas}. Q is given by:

$$Q = Q_{meas} \cdot f_{sat} \cdot f_{pol} \cdot f_{conf} \qquad (2)$$

where:

f_{sat} corrects for the lack of saturation due to ion recombination;

f_{pol} is the polarity correction;

f_{conf} is the configuration correction.

Therefore air kerma, K_a, is defined as:

$$K_a = \frac{Q_{meas}}{m} \cdot \frac{W_{air}}{e} \cdot F \qquad (3)$$

where:

Q_{meas} is the charge collected;

m is the known mass of air in the cavity;

W_{air} is the energy to create a ion pair in air;

e is the electron charge;

F is the chamber correction factor.

The chamber correction factor is expressed as a ratio

$$F = \frac{K_a}{(Q_{meas}/m) \cdot (W_{air}/e)} \qquad (4)$$

in which the denominator is the absorbed dose to the air in the chamber cavity, calculated by Monte Carlo for a given beam, and the numerator is the air kerma.

3 MONTE CARLO CALCULATIONS

The EGS4/BEAM Monte Carlo system was used to model the beams from the Mainance and Theratron units. Phase space data representing the simulated beam emerging from the adjustable collimator of the Theratron were validated by comparing the mean air kerma on axis with measurements using an NPL secondary standard ionisation chamber, as a function of aperture setting. The Mainance unit has a fixed collimator. These phase space data were taken as input to EGSnrc simulations, calculating the dose to the air cavity for a variety of chambers that were idealised in various ways.

For each beam, the first simulation gave the dose in a more or less realistic model of the cavity chamber, with appropriate electron and photon transport cut-offs. The last simulation obtained the air kerma as the dose to a thin slab of air at the position of the chamber without electron transport. The ratio of these two doses is the required chamber correction factor.

In a cavity theory analysis this overall correction is expressed as a product of factors, one for each physical effect. The Monte Carlo result was factorised in an equivalent way by simulating chambers in which these physical effects were turned on one by one.

Starting from cavity dose in the realistic chamber with a stem (0), the changes were:

1) Remove the chamber stem

2) Exclude the dose from scattered photons

3) Compensate for wall attenuation of primary photons

4) Replace the insulators by graphite of matching density

5) Replace the air by graphite gas

6) Replace all materials by air of matching density

7) Turn off electron transport

8) Replace the actual chamber geometry by a thin slab of air in air of normal density

The ratios of cavity dose for successive calculations in this sequence produce the following factors:

- The stem scatter correction, f_{ss} is given by the ratio (1) / (0)

- The wall scatter correction is (2) / (1)

- The wall attenuation correction is (3) / (2)

- The overall wall correction, f_{wall}, is (3) / (1)
- The non-graphite materials correction, f_{mat} is (4) / (3)
- The product of a fluence perturbation correction and the ratio of the mean stopping powers of graphite and air, $\overline{S}(\Delta)_{air}^{C} \cdot f_{fl}$ is (5) / (4)
- The ratio of mass-energy absorption coefficients, $(\mu_{en}/\rho)_{C}^{air}$ is (6) / (5)
- The correction due to bremsstrahlung losses, $(1-g_{air})^{-1}$ is (7) / (6)
- The beam non-uniformity correction, f_{pn} is (8) / (7)
- The overall chamber correction, F_{MC} is (8) / (0)

This reproduces the result of a cavity theory analysis in the form:

$$F_{MC} = \overline{S}(\Delta)_{air}^{C} \cdot f_{fl} \cdot (\mu_{en}/\rho)_{C}^{air} \cdot (1-g_{air})^{-1} \cdot f_{ss} \cdot f_{wall} \cdot f_{mat} \cdot f_{pn} \qquad (5)$$

For purposes of consistency in Table 1, $(1-g_{air})^{-1}$, f_{ss} and f_{pn} are excluded from the correction factor $\widetilde{F}$. And so,

$$F_{MC} = \widetilde{F} \cdot (1-g_{air})^{-1} \cdot f_{pn} \cdot f_{ss} \qquad (6)$$

For this evaluation: values given for g_{air} are tabulated values, not the values calculated by Monte Carlo techniques; values given for f_{ss} are Monte Carlo calculated values retained from previous work.

And so,

$$F = F_{MC} \cdot f_{sat} \cdot f_{pol} \cdot f_{conf} \qquad (7)$$

Values for the corrections for saturation, polarity and configuration effects have been retained from previous work.

4 RESULTS

	1969 - 1992		1992 - 2009				Post 2009		
	1 MV Van de Graaff	2 MV Van de Graaff	1 MV Van de Graaff	2 MV Van de Graaff	^{137}Cs Mainance	^{60}Co Mainance	^{137}Cs Mainance	^{60}Co Mainance	^{60}Co Theratron
W_{air}/e (JC^{-1})	33.85	33.85	33.97	33.97	33.97	33.97	33.97	33.97	33.97
g_{air}	0.002	0.005	0.0015	0.0030	0.0016	0.0032	0.0016	0.0032	0.0032
$\bar{S}(\Delta)^C_{air}$	1.0079	1.0032	-	1.0018	-	0.9984	1.0076	1.0000	1.0003
f_{fl}	-	-	-	0.9965	-	0.9960			
$(\mu_{en}/\rho)^{air}_C$	0.9992	0.9994	-	0.9992	-	0.9989	1.0001	1.0003	0.9999
f_{wall}	1.0200	1.0176	-	1.0161	-	1.0133	1.0182	1.0130	1.0130
$f_{el.equil.}$	1.0000	1.0019	-	-	-	-	-	-	-
f_{other}	-	-	-	0.9969	-	0.9997	-	-	-
f_{mat}	-	-	-	-	-	-	1.0032	1.0028	1.0031
$\tilde{F}$	-	-	1.0198	1.0104	1.0198	1.0062	1.0293	1.0161	1.0163
f_{pn}	-	-	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
f_{ss}	0.9975	0.9975	0.9964	0.9973	0.9952	0.9971	0.9952	0.9971	0.9971
F_{MC}	-	-	-	-	-	-	1.0260	1.0164	1.0166
f_{sat}	1.0020	1.0020	1.0020	1.0020	1.0020	1.0020	1.0020	1.0020	1.0020
f_{pol}	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995
f_{conf}	1.0010	1.0010	1.0010	1.0010	1.0010	1.0010	1.0010	1.0010	1.0010
$F^{(*)}$	1.0293	1.0273	1.0202	1.0132	1.0191	1.0090	1.0286	1.0190	1.0192

Table 1: Air kerma cavity standard correction factors

All correction factors in Table 1 exclude the additional correction for humidity that was introduced into the calibration factors in 1979 [13].
$^{(*)}$ In order to provide consistency between previous and new work this factor includes the correction due to bremsstrahlung losses in all cases.

5 UNCERTAINTIES

Values for the standard uncertainties on the newest results are listed in Table 2. The type A uncertainties for the various factors are correlated, leading to a reduced type A uncertainty in the overall correction.

Estimates for the Type B uncertainties in $(\mu_{en}/\rho)_C^{air}$ and $\bar{S}(\Delta)_{air}^C$ have been taken from Rapport BIPM-99/12, Comparison of the air kerma standards of the NRC and the BIPM for ^{60}Co γ-rays. The reduced uncertainty in product of the stopping power ratio with W_{air}/e is listed here.

Correction Factor	Type A (%)	Type B (%)	Combined (%)
g_{air}	-	0.02	0.02
$\bar{S}(\Delta)_{air}^C \cdot f_{fl}$	0.06	0.12	0.13
$(\mu_{en}/\rho)_C^{air}$	0.05	0.10	0.11
f_{wall}	0.01	0.05	0.05
f_{mat}	0.04	0.05	0.06
$\tilde{F}$	0.03	0.17	0.19
f_{pn}	0.05	0.1	0.11
f_{ss}	0.02	<<0.1	0.02
$f_{sat} \cdot f_{pol} \cdot f_{conf}$	-	0.15	0.15
F	0.06	0.25	0.27

Table 2: Standard uncertainties for the air kerma cavity standard

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