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# Changes to the NPL air kerma standard for $^{60}$Co γ-rays

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## 1 Summary

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. Corrections to the response of these chambers account for wall attenuation, scatter, lack of air-equivalence, etc. and were last revised in 1992, when we adopted values based on the results of EGS4/PRESTA Monte Carlo simulations. Since 1996, this standard has been used in $^{60}$Co γ-rays either from a Mobaltron unit (1996-2000) or from a Theratron 780C (2000 to date). The commissioning of the Theratron unit, but especially the release of the EGSnrc code system, provided an opportunity to revisit the corrections to this standard.

Prior to 1992, 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. In this model 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. Instead, the chamber wall effect was calculated using Monte Carlo, with results checked against cavity ionisation theory, and the correction factors adopted in 1992 were based on the MC calculations of dose to the air in the chamber cavity in the 2 MV X-ray beam. Further calculations were made of the corrections required for protection-level γ-ray beams from $^{137}$Cs and $^{60}$Co sources in the Mainance facility at NPL[1]. The net effect of the changes at this time was to reduce the NPL air kerma standard by 1% at therapy-level and by 1.4% at protection-level.

Therapy-level calibrations were moved to the Mobaltron facility after the 2MV Van de Graaff X-ray generator failed in 1996. 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 (such as PRESTA II) were available in general purpose Monte Carlo codes. This re-evaluation has now been completed using EGSnrc, as described below, and adoption of the new corrections would result in an increase of the NPL air kerma standard by 1% for both therapy and protection levels.

For the reasons explained in CCRI(I)/03-06, the implementation of this change will be delayed until 2004, when the existing primary standard cavity chambers will be replaced.

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[1] Before 1992, these corrections had been assumed to be identical to the factors used in 1 MV and 2 MV X-rays, respectively.

## 2 Definition of the cavity chamber correction

The air kerma at the position of the chamber is given by:

$$K_a = \frac{Q}{m} \cdot \frac{W}{e} \cdot F_{MC} \qquad (3.1)$$

where: $Q$ is the charge produced by ionisation in the cavity

$m$ is the known mass of air in the cavity

$W$ is the energy to create an ion pair

$e$ is the electron charge

$F_{MC}$ is the chamber correction factor which we calculate by Monte Carlo

Various effects prevent us from identifying $Q$ with the charge actually collected. The measured charge $Q_{meas}$ is given by:

$$Q = Q_{meas} \cdot f_{sat} \cdot f_{pol} \cdot f_{conf} \qquad (3.2)$$

where: $f_{sat}$ corrects for lack of saturation due to ion recombination

$f_{pol}$ is the polarity correction

$f_{conf}$ is the configuration correction[2]

The chamber correction factor is expressed as a ratio

$$F_{MC} = {K_a}\big/{(Q/m)\cdot(W/e)} \qquad (3.3)$$

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 The Monte Carlo systems used

The EGS4/BEAM Monte Carlo system was used to model the beams from the Theratron and Mainance 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 which were idealised in various ways. EGSnrc, which represents a significant revision to the predecessor EGS4/PRESTA, has been extensively but perhaps not yet exhaustively benchmarked: at the time of writing there are some details of our simulation results that deserve further investigation and the corrections presented in Table 1 should be regarded as preliminary.

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 cutoffs. 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.

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[2] 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. The design of the replacement chambers is such that this correction will not be required.

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 (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 factor 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, $\overline{S}(\Delta)_{air}^{G} \cdot f_{fl}$ is (5) / (4)
- the ratio of mass-energy absorption coefficients, $(\mu_{en}/\rho)_{G}^{air}$ is (6) / (5)
- the correction due to bremsstrahlung losses, $(1-g)^{-1}$ 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:

$$F_{MC} = \overline{S}(\Delta)_{G,air} \cdot f_{fl} \cdot (\mu_{en}/\rho)_{G}^{air} \cdot (1-g)^{-1} f_{wall} \cdot f_{mat} \cdot f_{pn} \cdot f_{ss} \qquad (3.3)$$

## 4 Results

The individual correction factors are listed in the first table. The pre-1992 corrections include $f_{el.equil.}$, which allows for incomplete build up in the higher energy beam. The correction $f_{other}$ was included in the post-1992 corrections to allow for a residual discrepancy between the various Monte Carlo simulations contributing to the overall correction. The present results are internally consistent and need no such correction. The correction for stem scatter, which is based on measurements with a dummy stem, has not changed and is not listed here.

| **Date:** | **Pre 1992** | **Post 1992 (EGS4/Presta)** | | **EGSnrc** |
|---|---|---|---|---|
| **Beam:** | 2 MV ≡ $^{60}$Co | 2 MV | $^{60}$Co | $^{60}$Co |
| $W/e$ | 33.85 | 33.97 | 33.97 | 33.97 |
| $f_{wall}$ | 1.0176 | 1.0161 | 1.0133 | 1.0130 |
| $f_{mat}$ | - | - | - | 1.0031 |
| $\bar{S}(\Delta)_{air}^{G}$ | 1.0032 | 1.0018 | 0.9984 | 1.0003 |
| $f_{fl}$ | - | 0.9965 | 0.9960 | |
| $(\mu_{en}/\rho)_{G}^{air}$ | 0.9994 | 0.9992 | 0.9989 | 0.9999 |
| $(1-g)^{-1}$ | 1.005 | 1.003 | 1.003 | 1.0024 |
| $f_{pn}$ | - | 1.0000 | 1.0000 | |
| $f_{el.equil.}$ | 1.0019 | - | - | - |
| $f_{other}$ | - | 0.9969 | 0.9997 | - |

Table 1 Air kerma cavity standard correction factors

Provisional values for the standard uncertainties on the new results are listed in the second table. The type A uncertainties for the various factors are correlated, leading to a reduced type A uncertainty in the overall correction.

| Correction Factor | Type A (%) | Type B (%) | Combined (%) |
|---|---|---|---|
| $\left[{}_m\overline{S}_{air}^{C}(\Delta)\right]_{SA}\cdot f_{fl}$ | 0.06 | 0.12 | 0.13 |
| $\left(\overline{\mu_{en}/\rho}\right)_{C}^{air}$ | 0.05 | 0.10 | 0.11 |
| $f_{wall}$ | 0.01 | 0.05 | 0.05 |
| $f_{mat}$ | 0.04 | 0.05 | 0.06 |
| $f_{pn}$ | 0.05 | 0.1 | 0.11 |
| $F_{MC}$ | **0.03** | **0.20** | **0.20** |

Table 2 Standard uncertainties of the air kerma cavity standard correction factors

Estimates for the Type B uncertainties in $\left(\overline{\mu_{en}/\rho}\right)_{C}^{air}$ and $\left[{}_m\overline{S}_{air}^{C}(\Delta)\right]_{SA}$ 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 $W/e$ is listed here.