**New BIPM absorbed-dose standard for medium-energy x-rays**

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**1 Introduction**

A number of NMIs are now using water calorimeter standards to determined absorbed dose to water in the medium-energy x-ray range and there is a growing need for comparisons in this area. To provide a robust and stable long-term reference the BIPM has developed an ionometric primary standard for absorbed dose to water for the CCRI reference qualities from 100 kV to 250 kV. The standard will be used to make indirect comparisons of NMI standards through the calibration of waterproof transfer chambers at 2 g cm–2 in a water phantom. A calibration service for national secondary standards will also be offered.

**2 Outline of the method**

The standard is based on the existing free-air chamber standard for the determination of air kerma, *K*air. A waterproof transfer chamber is first positioned in air at the reference distance of 1200 mm and the ionization charge *Q*air measured (the chamber calibration coefficient therefore being *NK*,air = *K*air/*Q*air,). The chamber is then positioned at the reference depth of 2 g cm–2 in water, while remaining at the reference distance, and the ionization charge *Q*w is measured. The absorbed dose to water, *D*w, at the reference distance and depth is derived using

 (1)

where *k*rn is a measured correction for the radial non-uniformity in water over the dimensions of the air cavity (an effect that is negligible in air). The conversion factor in parenthesis, referred to henceforth as *C*MC, is in effect a ratio of ‘calibration coefficients’, water to air, calculated using the Monte Carlo method; *D*cav,w represents the calculated cavity dose for the chamber in water and *D*cav,air that for the chamber in air. Although expressed in different terms, the method has at least in principle much in common with that used in codes of practice based on air kerma. However, the self-consistent and detailed implementation is such that the uncertainties are reduced to a level that is comparable with existing standards based on water calorimetry. In particular:

i The spectra used for the calculations contain the full phase-space information and are calculated from a simulation of the BIPM x-ray tube, inherent filtration, collimation and added filtration;

ii The geometries of the transfer chambers are simulated in detail, as is the geometry of the PMMA water phantom front face and entrance window;

iii The choice of detailed transport parameters results in reliable cavity-dose calculations;

iv Evaluation of *D*w using transfer chambers of different type, as well as several chambers of the same type, allows a more robust determination and a better estimate of the uncertainty;

v An arrangement to reproducibly position ionization chambers at the reference depth in water to better than 0.02 mm results in highly reproducible charge ratios *Q*w/*Q*air.

**3 Transfer ionization chambers and measurement of charge ratios**

The initial plan was to use two waterproof parallel-plate chambers constructed at the BIPM, similar in design to the primary standard for air kerma in 60Co radiation, one constructed from graphite and the other from air-equivalent plastic. However, these chambers were found to be unsuitable, firstly because the radial non-uniformity correction in water approached 2 % and secondly because the air-kerma calibration coefficient *NK*,air changed by around 20 % over the range from 100 kV to 250 kV.

Instead, two commercial chamber types have been used; an Exradin A12 chamber, for which *NK*,air is constant to within 1 % over the range of interest, and a PTW30013 chamber, with a response that changes by only 0.2 % over this range. In fact, three PTW30013 chambers, kindly on loan from the PTB, were used to assess the chamber-to-chamber reproducibility of the *Q*w/*Q*air ratio for a given chamber type. The result of this test was a standard deviation in the ratio *Q*w/*Q*air of typically 0.06 %.

The reproducibility of the *Q*w/*Q*air measurement depends critically on the positioning of the chamber in water. The adopted arrangement positions the water phantom on a support that can be raised and lowered (see Figure 1). With the phantom lowered, a chamber supported from above is positioned in air at the reference distance using a fixed micrometer system. The water phantom is then raised to the correct height and its axial position adjusted so that the chamber is at 2 g cm–2, measured using the same micrometer touching the phantom window. The depth in g cm–2 is evaluated taking into account the PMMA window of thickness 1.677 mm and nominal density 1.19 g cm–3 and the water density of 0.9982 g cm–3 at 20 °C. The reproducibility of the depth positioning is below 0.02 mm and the window position has been shown to be stable in time at the 0.01 mm level. The results for the measured charge ratios are included in Table 1.

Figure 1. The Exradin A12 transfer chamber in the raised water phantom. The axial positions of the chamber and phantom are independently set at the 0.02 mm level.

**4 Monte Carlo calculations**

The calculations were made using the PENELOPE code (Salvat *et al* 2009). The critical elements of the ionization chambers (collector, wall, base) were simulated in detail and the chamber stem in moderate detail. Additional calculations with modified collector diameter and wall thickness are discussed in Section 5. The 20 cm cubic water phantom was simulated with attention paid to the details of the window and the water filling height.

Phase-space files of photons in the plane 900 mm from the focus were prepared from a simulation of the x-ray tube. A parallel electron source producing a 4.3 mm square focal spot (as seen from the reference plane) was incident on a tungsten target (with angle 20°) and the resulting photon fluence passed through a 3 mm beryllium window and lead collimator (13.88 mm in diameter, chosen to give the measured field diameter of 98 mm at 1200 mm distance). The BIPM filtration corresponding to the CCRI reference qualities was simulated in detail. Because of the relative inefficiency of bremsstrahlung production at these energies and the limited cone of interest, only around 5 106 photons were produced for each energy, which ultimately limited the statistical uncertainty of the calculations of cavity dose. The resulting spectra compare well with those obtained by calculation using the SpekCalc software (Poludniowski *et al* 2009), and reasonably well with those measured for the previous BIPM x-ray tube (pre-2004). Uncertainties arising from differences are discussed in Section 5.

The air kerma *K*air,MC (per incident photon) in the reference plane was calculated for a cylinder 30 mm in thickness and of diameter 10 mm corresponding to the aperture of the BIPM free-air chamber. This calculation is relatively efficient because no electron transport is necessary. Calculation of the absorbed dose *D*w,MC at 2 g cm–2 is potentially much less efficient, for two reasons. Firstly, for radial non-uniformity effects to cancel, the calculation was made for a smaller, rectangular cross section with dimensions corresponding to the diameter and cavity length of a Farmer-type chamber. Secondly, electron transport is normally required for an absorbed-dose calculation. However, it was shown that switching off electron transport changed the absorbed dose by less than 0.04 %. This demonstrates that, for these energies, charged-particle equilibrium (CPE) is well approximated and bremsstrahlung production is negligible. In other words, it is sufficient to calculate the kerma in water.

The cavity doses *D*cav,air and *D*cav,w were calculated with relatively detailed electron transport (PENELOPE parameters *C*1 = *C*2 = 0.05, *W*cc = 2 keV) down to 2 keV in the air cavity and in all surfaces in contact with the cavity. The uncertainty arising from the choice of transport parameters is discussed in Section 5.

The results for the calculated factor *C*MC are given in Table 1 for each of the two chamber types along with the measured charge ratios *Q*w/*Q*air, the measured radial non-uniformity corrections *k*rn and the statistical standard uncertainty **A of each parameter. The resulting ratios *D*w/*K*air that represent the combined conversion from air kerma to absorbed dose to water are also given. Agreement in the values for *D*w/*K*air between the two chambers is within the statistical uncertainty for two of the four qualities. Differences are discussed in Section 5 in relation to the chamber geometry simulations.

**Table 1. Results for each transfer chamber type of the conversion from air kerma to absorbed dose in water.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | 100 kV | 135 kV | 180 kV | 250 kV |
|  | value | **A / % | value | **A / % | value | **A / % | value | **A / % |
| *Exradin A12* |  |  |  |  |  |  |  |  |
| *C*MC | 1.0356 | 0.12 | 1.0667 | 0.12 | 1.0825 | 0.12 | 1.1012 | 0.12 |
| *Q*w/*Q*air | 1.1406 | 0.03 | 1.3355 | 0.08 | 1.3276 | 0.06 | 1.2359 | 0.07 |
| *k*rn | 1.0035 | 0.03 | 1.0036 | 0.03 | 1.0033 | 0.03 | 1.0026 | 0.03 |
| *D*w/*K*air | 1.1853 | 0.13 | 1.4297 | 0.15 | 1.4419 | 0.14 | 1.3645 | 0.14 |
| *PTW30013* |  |  |  |  |  |  |  |  |
| *C*MC | 1.0405 | 0.12 | 1.0717 | 0.12 | 1.0876 | 0.12 | 1.1064 | 0.12 |
| *Q*w/*Q*air | 1.1331 | 0.06 | 1.3294 | 0.07 | 1.3237 | 0.05 | 1.2355 | 0.02 |
| *k*rn | 1.0031 | 0.03 | 1.0031 | 0.03 | 1.0029 | 0.03 | 1.0023 | 0.03 |
| *D*w/*K*air | 1.1826 | 0.14 | 1.4291 | 0.14 | 1.4438 | 0.13 | 1.3701 | 0.13 |

**5 Uncertainty analysis**

In addition to the elements listed in Section 2 aimed at reducing uncertainties, the conversion factor *C*MC (in parenthesis in equation (1)) is a ratio of ratios and as such many potential uncertainties cancel to first order. It can be written analytically as

 . (2)

Here, the numerator represents calculations for the transfer chamber in water, and the denominator for those in air. The *s*wall,air are stopping-power ratios for the chamber wall material and the cavity air, and the *p*cav are perturbation factors for deviations from ideal Bragg-Gray behavior. These will clearly cancel to a large extent for the water-to-air ratio, with no uncertainty arising from the choice of stopping-power data used. The ** terms are each a ratio of absorbed dose to collision kerma; it was shown in Section 4 that for the medium-energy x-ray spectra CPE is well approximated and so the ** terms are all very close to unity with negligible uncertainty, as is the radiative loss (1gair). The photon fluence perturbation *ψ* due to the presence of the chamber will also be subject to significant cancellation and its uncertainty is assumed to be negligible. What remains are the two ratios of mass energy-absorption coefficients (*µ*en/**), and as (*µ*en/**)wall appears in both (and therefore largely cancels) we take their ratio to be (*µ*en/**)w,air.

Four components considered to remain significant are discussed below, namely the ratio (*µ*en/**)w,air as discussed above, the impact on *D*cav,w/*D*cav,air of choices regarding electron transport, the goodness of the chamber geometry modelling and the sensitivity to the incident spectra. The uncertainties evaluated by statistical (**A ) and non-statistical (**B) methods are presented in Table 2, which includes the uncertainty of the BIPM air-kerma determination. Note that the air-kerma determination for the purpose of the *D*w/*K*air evaluation incorporates the recent recommendations of ICRU Report 90 (ICRU 2016), namely an increase in the uncertainty of *W*air to 0.35 % and the inclusion of the correction factor *k*ii*k*W and its uncertainty of 0.05 %. The adopted values for *k*ii*k*W and their uncertainty are the subject of a separate report to the CCRI(I).

*5.1 Mass energy-absorption coefficients*

Uncertainties for mass energy-absorption coefficients and their ratios have been addressed in a number of recent works (Andreo *et al* 2012, ICRU 2016). Of interest for the present report is the specific case of (*µ*en/**)w,air for medium-energy x-ray spectra. For the evaluation of uncertainty, we can make use of the corresponding ratio of mass attenuation coefficients (*µ*/**)w,air. ICRU Report 90 gives monoenergetic *µ*/** values for water and air, calculated by different authors using different models, for both the photoelectric effect (five models) and for Compton scattering (three models). From the spread of these values we can make deductions regarding the uncertainties.

Importantly, we can also calculate the ratio (*µ*/**)w,air for a given model to provide information on the extent to which the uncertainty is reduced through correlation. The results show large reductions in uncertainty such that, when taking maximum differences (rather than standard deviations), the uncertainty of the spectral value for (*µ*en/**)w,air is around 0.2 % at 100 kV, reducing to around 0.1 % at 250 kV[[1]](#footnote-1). The value 0.25 % included in Table 2 is more conservative than the estimate of 0.15 % for 100 kV given by Andreo *et al*, who looked not only at different data sets but also included variations arising from different Monte Carlo implementations.

Note that the present work included a series of measurements of attenuation in slabs of materials, and corresponding Monte Carlo simulations of the measurement apparatus, to provide specific information on the extent to which the Monte Carlo code employed reproduces the measured mass attenuation ratio (*µ*/**)w,air for the medium-energy x-ray spectra at the BIPM. However, while agreement between measurements and calculations was demonstrated, it was not possible to reduce the experimental uncertainty below the 1.0 % level.

**Table 2. Standard uncertainty components for determination of absorbed dose to water**

|  |  |  |
| --- | --- | --- |
| Component | Type A**A / % | Type B**B / % |
| *Air-kerma standard* |  |
| Existing FAC (excl. *W*air) | 0.04 | 0.12 |
| *W*air | - | 0.35 |
| *k*ii*k*W | - | 0.05 |
| *Conversion measurements* |  |
| *Q*w/*Q*air | 0.06 | - |
| *k*rn | - | 0.03 |
| *Conversion calculations* |  |
| Statistical component of *C*MC | 0.12 | - |
| Data for (*µ*en/**)w,air | - | 0.25 |
| Electron transport | - | 0.10 |
| Chamber geometry | - | 0.25 |
| Incident spectra | - | 0.15 |
| ***Combined standard******uncertainty*** | **0.14** | **0.55** |
| ****c = 0.56** |

*5.2 Electron transport*

The choice of electron transport parameters influences only the cavity dose ratio *D*cav,w/*D*cav,air. Previous work for 60Co (Burns 2006) showed calculations using the selected parameters to agree with an ‘exact’ calculation, that is, an extremely slow calculation simulating every electron interaction, to better than 0.1 %. The present application is less demanding because for a given transfer chamber only the ratio *D*cav,w/*D*cav,air is of interest and any deficiency in the calculation of *D*cav,w will have a corresponding effect on *D*cav,air. The resulting uncertainty of the ratio is likely to be well below the statistical uncertainty of 0.12 % in *C*MC. A conservative value of 0.10 % is included in Table 2.

*5.3 Chamber geometry*

More explicit information on the agreement between the measured charge ratios *Q*w/*Q*air and the calculated cavity dose ratios *D*cav,w/*D*cav,air is given in Table 3, where the ratio measured-to-calculated is expressed as a correction factor *k*MC . Equation (1) becomes

 , (3)

where, in effect, *k*MC corrects the calculated ratio (*D*w/*K*air)MC to yield the best estimate *D*w/*K*air. All values for *k*MC are greater than unity, reflecting the fact that *D*w,MC is always low relative to *K*air,MC. Various reasons for this can be postulated, for example an overestimate of the attenuation over 2 g cm–2 of water, or an underestimate of the scatter contribution at this depth, including the effect of field-size. Such differences are not problematic, because an underestimation of *D*w,MC for such reasons is accompanied by a corresponding underestimate of *D*cav,w. This cancellation is inherent in the method and is essentially the reason why transfer chambers are used (otherwise *D*w/*K*air could be taken purely from the Monte Carlo calculation).

**Table 3. Comparison of the measured and calculated values of the chamber response ratios water to air, expressed as the correction factor *k*MC.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | 100 kV | 135 kV | 180 kV | 250 kV |
|  | value | **A / % | value | **A / % | value | **A / % | value | **A / % |
| *Exradin A12* |  |  |  |  |  |  |  |  |
| *Q*w/*Q*air | 1.1406 | 0.03 | 1.3355 | 0.08 | 1.3276 | 0.06 | 1.2359 | 0.07 |
| *D*cav,w/*D*cav,air | 1.1352 | 0.14 | 1.3183 | 0.16 | 1.3082 | 0.14 | 1.2193 | 0.12 |
| *k*MC | 1.0048 | 0.14 | 1.0130 | 0.18 | 1.0148 | 0.16 | 1.0136 | 0.14 |
| *PTW30013* |  |  |  |  |  |  |  |  |
| *Q*w/*Q*air | 1.1331 | 0.06 | 1.3294 | 0.07 | 1.3237 | 0.05 | 1.2355 | 0.02 |
| *D*cav,w/*D*cav,air | 1.1286 | 0.16 | 1.3139 | 0.22 | 1.2987 | 0.17 | 1.2138 | 0.15 |
| *k*MC | 1.0040 | 0.17 | 1.0118 | 0.23 | 1.0193 | 0.18 | 1.0179 | 0.15 |

More important is any difference in *k*MC for the two transfer chamber types, for a given beam quality, because such a difference cannot be explained as above. Table 3 shows deviations larger than the combined statistical uncertainties for two qualities, 180 kV and 250 kV. The additional uncertainty required to render the data set consistent is around 0.25 %, which provides an estimate for effects related to chamber geometry.

The most sensitive elements of the chamber simulations are likely to be the dimensions and materials of the central collector and chamber wall. Additional calculations were made for the PTW30013 chamber type with its aluminium collector diameter reduced from 1.1 mm to 1.0 mm. While this reduced both *D*cav,air and *D*cav,w by around 2.5 % at 100 kV (an effect progressively decreasing to 0.5 % at 250 kV), the ratio *D*cav,w/*D*cav,air did not change by more than 0.4 % for any quality. Given that the manufacturing tolerance for the collector is probably below 0.03 mm, any difference between the assumed diameter of 1.1 mm and the actual diameter of a given chamber is not likely to introduce an error of more than 0.15 %. Similar calculations for the chamber wall did not show any significant effect. The uncertainty of 0.25 % noted in the previous paragraph, which inherently takes into account the possibilities discussed here, is included in Table 2.

*5.4 Representation of incident spectra*

Differences between the true spectra and the calculated phase-space representations are most likely to influence the results through the ratio (*µ*en/**)w,air, as most other effects cancel to first order. To estimate the sensitivity, the simulated spectra and those calculated using SpekCalc (Poludniowski *et al* 2009) were compared with the spectra measured at the BIPM (in fact these measurements were made for the pre-2004 x-ray tube at the BIPM, for which the qualities were very similar). The standard deviation of the three results for (*µ*en/**)w,air at each beam quality was in the range from 0.06 % to 0.14 %. A conservative standard uncertainty of 0.15 % is included in Table 2.

**6 Results and discussion**

The final results for the conversion from *K*air to *D*w , referred to as *C*w,air, are summarized in Table 4. The value of *C*w,air for each quality is the arithmetic mean of the *D*w/*K*air values obtained for the two transfer chamber types in Table 1. The combined standard uncertainties **A and **B are summarized from Table 2.

**Table 4. The conversion factor from air kerma to absorbed dose to water for the BIPM standard.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | 100 kV | 135 kV | 180 kV | 250 kV | **A / % | **B / % |
| ***C*w,air** | **1.1839** | **1.4293** | **1.4427** | **1.3672** | **0.13** | **0.40** |

Measurements for a comparison with the PTB water calorimeter standard have been made and are the subject of a separate report to the CCRI(I). In the meantime, a comparison is made with the absorbed dose to water obtained using two codes of practice based on air kerma. The results are shown in Figure 1, where the ordinate value of unity represents the BIPM standard and the dotted lines represent the combined standard uncertainty **c.

**Figure 1.** Comparison of the BIPM absorbed-dose standard with the codes of practice AAPM TG-61 and IAEA TRS-277. The solid line represents the BIPM standard and the dotted lines the limits of the standard uncertainty.

For the AAPM TG-61 protocol (Ma *et al* 2001), the comparison is made for the Exradin A12 chamber using the measured charge ratios *Q*w/*Q*air from Table 3, the *C*w,air values from Table 4, the (*µ*en/**)w,air values from Table VII of TG-61 and the chamber perturbation factors *PQ*,cham from Table VIII for the Exradin A12 chamber type (the PTW30013 chamber type is not included in the protocol). In the IAEA TRS‑277 code (IAEA 1997), thimble chambers are treated generically. We see already in Table 3 a difference of up to 0.7 % in *Q*w/*Q*air for the two thimble chambers at a given quality; for the comparison with TRS-277, the mean is used. The values for (*µ*en/**)w,air are taken from Table XIV of TRS-277 and those for the perturbation factor *p*u from the revised Table XV (with a stated standard uncertainty of 2 %).

With the exception of the 100 kV result for TRS-277, the codes of practice agree with the BIPM determination at the 1 % level, which is well within the stated uncertainty of the codes. Consequently, calibrations traceable to the new standard will not result in a significant change in the reference absorbed dose. However, the uncertainty is reduced by a factor of around four.

**References**

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1. For 50 keV photons in low-Z materials, the cross section for the photoeffect is around one tenth of that for the Compton effect. However, under these conditions the photoeffect transfers around ten times more energy to the medium per interaction. Furthermore, the present study indicates that correlation in the uncertainty between air and water is significantly less for the photoeffect. Consequently, it is the photoeffect that dominates the uncertainty at 50 keV, and indeed for the 100 kV and 135 kV spectra. [↑](#footnote-ref-1)