IMPLICATIONS OF X-RAY TUBE PARAMETER DEVIATIONS IN X-RAY REFERENCE FIELDS

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For the purpose of radiation protection, ICRU Report 57/ICRP Publication 74 provides a list of monoenergetic conversion coefficients to be used with, among others, photon reference fields generated with X-ray tubes. A comprehensive definition of these photon reference fields can be found in international standard ISO 4037; however, it lacks thorough indication of the allowed deviations of essential parameters that influence these X-ray reference fields. These parameters are the high-voltage tube potential, the thickness of the beryllium window and the purity and thickness of the filter materials used to create different radiation qualities. Small variations of these parameters can lead to significant changes in the created X-ray spectra and, hence, the spectra-dependent conversion coefficients for phantom-related radiation-protection quantities. This can lead to situations in which the conversion coefficients listed in ISO 4037 cannot be used, resulting in time-consuming spectrometry measurements. In this work, the impact on the resulting conversion coefficients is investigated using a simplified mathematical approximation model. The findings are validated with an independent X-ray spectra calculation programme. As a result, well-founded upper limit values on the allowed deviations of the essential X-ray tube parameters are proposed to be used in a future revision of ISO 4037.

INTRODUCTION

Conversion coefficients are extensively used in practical radiation protection to obtain the dose (rate) of a given radiation field: the air kerma free-in-air is measured and then converted into the phantom-related quantities $H^*(10)$, $H_p(10)$, $H'(3)$, $H_p(3)$, $H'(0.07)$ and $H_p(0.07)$. To determine the values of these conversion coefficients, in-depth knowledge about the fluence spectra of the radiation field is necessary. By interpolating the monoenergetic sampling points of the conversion coefficients and integrating over a range of energies, the kerma and the dose equivalent spectra can be obtained and the conversion coefficients can be derived (see below). It is not always possible to individually determine the conversion coefficients for a given X-ray field and, hence, the values stated in international standard ISO 4037 are often used. This is a common practice and adequate when the radiation fields match the photon reference fields, as described in the first part of ISO 4037⁽¹⁾. However, if differences in the fluence spectra exist between the actual radiation field and the ISO reference field, depending on the phantom definition depth, the resulting conversion coefficients may differ strongly. As a result, the conversion coefficients of ISO 4037 cannot be used offhandedly for arbitrary photon radiation fields. The essential parameters that, in combination, define the characteristics of the resulting fluence spectrum are (1) the high-voltage tube potential (which defines the maximum energy of the emitted photons), (2) material and thickness of both, the tube window (inherent filtration) and (3) the additional filtration and (4) the purity of the filtration material. In this paper, the

authors show, by how much each of the essential parameters may be varied to change the resulting conversion coefficients by at most 2 %. Since the conversion coefficients are also dependent on the phantom definition depth, all results are shown for the depths 0.07, 3 and 10 mm. Based on these investigations, it was proposed that new upper limit values for the allowed parameter variations for ISO photon reference fields such that the listed conversion coefficients can safely be used.

The structure of this paper is as follows: the section Conversion Coefficients gives a general description of the derivation of the conversion coefficients both monoenergetic and for spectra. A simplified mathematical method is introduced, and the effect of additional material layers on the conversion coefficients is described. After that, the validation process is explained. In the section Results, the deviations that lead to a change of the conversion coefficients of 2 % are shown and upper limit values are proposed. In the Discussion section, the retrieved upper limit values are summarised and compared with the advice given in the current version of ISO 4037. The findings are summarised in Conclusion.

CONVERSION COEFFICIENTS

This section explains how the different conversion coefficients are determined and introduces a simplified mathematical model that approximates the spectra by trapeziums and allows for a time-saving calculation of the effects on the conversion coefficients. References to the data used for this work are

given, and the validation method used to confirm the authors' results is explained.

Monoenergetic conversion coefficients

Monoenergetic conversion coefficients, h , are the basis for the conversion of collisional air kerma free-in-air, K_a , into the phantom-related quantities. The coefficients are given as a function of photon energy, E : $h(E)$. Different conversion coefficients are required for each of the radiation protection quantities defined for definition depths 10, 3 and 0.07 mm, for the different phantoms and for each angle of radiation incidence assuming unidirectional photon radiation. Their notation is as follows. The example $h_{pK}(d;E;\alpha)$ refers to the conversion coefficient from air kerma K_a to personal dose equivalent in the phantom definition depth d for monoenergetic and unidirectional photon radiation energy E , with an angle α between the reference direction of the dosimeter and the direction of radiation incidence. Conversion coefficients for the conversion from air kerma to ambient dose equivalent are denoted by $h_K^*(d;E)$ and those to directional dose equivalent by $h_K'(d;E)$.

Figure 1 shows examples of $h_{pK}(d;E;0^\circ)$ for $d = 0.07$, 3 and 10 mm as a function of energy. The monoenergetic conversion coefficients are determined through Monte-Carlo calculations, in which both the air kerma free-in-air and the radiation protection quantities are considered and their relation is computed.

Monoenergetic conversion coefficients are used in this work for the high-voltage tube potential investigations and are taken from the following references: $h_{pK}(10;E;0^\circ)$ and $h_{pK}(10;E;60^\circ)$ from ICRU and ICRP^(2, 3) for energies between 10 and 400 keV and Ankerhold⁽⁴⁾ for energies of < 7 keV. $h_{pK}(3;E;0^\circ)$ and $h_{pK}(3;E;60^\circ)$ are taken from Till *et al.*⁽⁵⁾ and Behrens⁽⁶⁾ for photon energies of < 5 keV. $h_{pK}(0.07;E;0^\circ)$ and $h_{pK}(0.07;E;60^\circ)$ are taken from ISO 4037-3⁽⁷⁾.

Figure 1. Monoenergetic conversion coefficients for phantom definition depths $d = 0.07$, 3 and 10 mm.

Determination of conversion coefficients for spectra

For parameters other than the high-voltage tube potential, the investigations are more complex. Since the influence of additional layers on the X-ray field depends on the energy, it is required to consider full spectra to investigate their effect on the resulting conversion coefficients. In the following, the authors show how the conversion coefficients for non-monoenergetic radiation qualities are determined.

The first step is the determination of the fluence spectrum of the photon field, $d\Phi/dE = \Phi_E(E)$. Multiplication with the (fluence-related) kerma factor, $k_\Phi(E)$, gives the kerma spectrum, dK_a/dE :

$$dK_a/dE = k_\Phi(E) \cdot \Phi_E(E), \quad (1)$$

with the kerma factor being defined as:

$$k_\Phi(E) = E \cdot \frac{\mu_{tr}(E) \cdot (1 - g)}{\rho}, \quad (2)$$

for each energy E . The quotient $\mu_{tr}(E)/\rho$ is the mass-energy transfer coefficient and g the bremsstrahlung loss. For photon energies within the X-ray range and for radiation free in air, the fraction of energy that is lost in bremsstrahlung is negligible so that $(1 - g) \approx 1$.

Multiplication of the kerma spectrum with the monoenergetic conversion coefficients for each of the phantom-related radiation quantities results in the dose equivalent spectrum, dH/dE [see, for example, Reference (6)]:

$$dH/dE = h(E) \cdot k_\Phi(E) \cdot \Phi_E(E). \quad (3)$$

Where appropriate, the angle of radiation incidence has to be taken into account.

The conversion coefficient $h(R)$ for a given radiation quality R is then simply the integral of the corresponding dose equivalent spectrum divided by the integral of the corresponding kerma spectrum:

$$h(R) = \frac{\int [dH(R)/dE]dE}{\int [dK_a(R)/dE]dE}. \quad (4)$$

The present work uses the spectra of Ankerhold⁽⁴⁾ either as they are, or modified, using conversion coefficients from Behrens⁽⁶⁾ and Till⁽⁵⁾. For small acceleration voltages, the fluence spectra are highly dependent on the distance between the radiation source and the point of measurement⁽⁴⁾, as the air in between absorbs a significant energy-dependent number of photons emitted by the source. Calibration of whole-body dosimeters on the ISO slab phantom is commonly performed in (at least) 2.5 m distance. Extremity and area dosimeters are calibrated at smaller distances, down to 1 m. In accordance with that, the authors' investigations considering

$h_{pK}(10;R;60^\circ)$ assume a distance of 2.5 m, investigations concerned with all the other conversion coefficients assume 1 m distance. Investigations on $h_{pK}(10;R;0^\circ)$ or $h_{pK}(3;R;0^\circ)$ are also valid for $h_K^*(10;R)$ or $h_K'(3;R)$, respectively and, therefore, are also performed at 1 m distance. The considered radiation qualities R are the N- and H-series as described in ISO 4037-3. The H-series has been expanded by the radiation qualities C-40, C-80 and C-150 from the C-series described in DIN 6818-1⁽⁸⁾. Apart from this extension, the C- and the H-series are identical. For simplicity, the authors expand the notation and denote the qualities of the extended series with H-40, H-80 and H-150.

Simplified method for the determination of conversion coefficients

The determination of the conversion coefficients according to Equation (4) is very time-consuming and goes beyond the scope of this work. Therefore, it is replaced by a simplified method that is described in the following, and a graphical representation is shown in Figure 2. The authors replace the kerma and dose equivalent spectra that were measured under reference conditions with simple rectangular approximations, whereby the maximum value of the measured bremsstrahlung spectrum is used as the height and the full-width half-maximum (FWHM) is used as the width of the rectangle (see the lightly shaded rectangles in Figure 2). The shaded areas denote the approximations to the kerma and the dose equivalent spectra. Variation of the thickness of a material is treated as an additional filtering and leads to spectra that are approximated by the darker shaded trapeziums. The quotient of these two trapeziums gives the resulting conversion coefficient.

The authors denote the maximum values (i.e. the height of the rectangles) with:

$$[dK_a(R)/dE]_{\max} \quad \text{and} \quad [dH(R)/dE]_{\max}, \quad (5)$$

Figure 2. Sketch of the mathematical model that is used to compute the conversion coefficients.

and the energies that correspond to the FWHM and represent the start and end values of the rectangle with:

$$E_{K_a,+1/2} \quad \text{and} \quad E_{K_a,-1/2}, \quad (6)$$

and, equally,

$$E_{H,+1/2} \quad \text{and} \quad E_{H,-1/2}. \quad (7)$$

With Equations (5–7), the conversion coefficient $h(R)$ can be simply computed as the ratio of the surfaces of the rectangles, replacing Equation (4):

$$h(R) = \frac{[dH(R)/dE]_{\max} \cdot [E_{H,+1/2} - E_{H,-1/2}]}{[dK_a(R)/dE]_{\max} \cdot [E_{K_a,+1/2} - E_{K_a,-1/2}]}. \quad (8)$$

The so-obtained conversion coefficients $h_{pK}(10;R;0^\circ)$ for radiation qualities N-15 to N-300 agree with the exception of N-60, within $\pm 2\%$ with the conversion coefficients that were obtained by integration [taken from reference (4)]. The deviation for radiation quality N-10 is $\pm 6\%$. Since the radiation qualities of the H-series contain strong fluorescence lines, which cannot be represented in the simple model, the deviation amounts up to $\pm 30\%$. It is important to note that these numbers represent the uncertainties on the absolute values of the conversion coefficients. Since only the relative change due to variations in the underlying spectra is of interest, these uncertainties are acceptable.

Influence of an additional material layer

The influence of an additional layer of a certain material (e.g. aluminium) and thickness l is estimated as follows. For each of the four characteristic energies $E_{K_a,+1/2}$, $E_{K_a,-1/2}$, $E_{H,+1/2}$ and $E_{H,-1/2}$, the transmission factors $T(E_{K_a,+1/2})$, $T(E_{K_a,-1/2})$, $T(E_{H,+1/2})$ and $T(E_{H,-1/2})$ for an additional material layer are determined using the software tool 'Photcoef'⁽⁹⁾. As all transmission factors are smaller than 1, the new areas are smaller than those of the rectangles and due to the energy dependence of the transmission factors they form trapeziums. The transmission factors were validated, using the recent version of the XCOM-programme from NIST⁽¹⁰⁾. No relevant differences between the two programmes were found.

With an additional layer of material, the resulting conversion coefficient $h(R_l)$ becomes as follows:

$$h(R_l) = \frac{[dH(R_l)/dE]_{\max} \cdot [E_{H,+1/2} - E_{H,-1/2}]}{[dK_a(R_l)/dE]_{\max} \cdot [E_{K_a,+1/2} - E_{K_a,-1/2}]}, \quad (9)$$

with

$$\begin{aligned} [dH(R_l)/dE]_{\max} &= [dH(R)/dE]_{\max} \\ &\cdot \frac{1}{2}[T(E_{H,+1/2}) + T(E_{H,-1/2})], \end{aligned} \quad (10)$$

and

$$\begin{aligned} [dK_a(R_l)/dE]_{\max} &= [dK_a(R)/dE]_{\max} \\ &\cdot \frac{1}{2}[T(E_{K_a,+1/2}) + T(E_{K_a,-1/2})]. \end{aligned} \quad (11)$$

In Figure 2, this resulting conversion coefficient corresponds to the quotient of the two stronger dyed trapeziums.

The relative change of the conversion coefficient due to the additional layer of material for radiation quality R is then as follows:

$$\Delta h(l) = \frac{h(R) - h(R_l)}{h(R)}. \quad (12)$$

By varying l , the authors find the thickness that leads to a change of the conversion coefficient of $|\Delta h(l)| = 2\%$. This simplified method is used to investigate the influence of the thickness of the filters, (im)purity of the used filter materials and the thickness of the exit window (inherent filtration) of the X-ray tube on the conversion coefficients $h_{pK}(10;R;0^\circ)$, $h_{pK}(10;R;60^\circ)$, $h_{pK}(3;R;0^\circ)$, $h_{pK}(3;R;60^\circ)$, $h_{pK}(0.07;R;0^\circ)$ and $h_{pK}(0.07;R;60^\circ)$ for the conversion of air kerma free-in-air to the relevant radiation protection quantities for given radiation qualities R.

Validation of the simplified mathematical method

The applied mathematical method is validated using an X-ray spectra calculation programme⁽¹¹⁾. For this, fluence spectra measured at the X-ray tubes of the Physikalisch-Technische Bundesanstalt (PTB)⁽⁴⁾ were used as input for a calculation programme that allows the simulation of filtered spectra with any desired material of arbitrary thickness. For both the unfiltered input spectrum and the filtered one, the appropriate conversion coefficients are computed in the way described earlier. The required monoenergetic conversion coefficient for each energy bin of a spectrum is obtained by a two-point linear interpolation of the sampling points from References (4–7) (for details on the interpolation, see Reference (4)).

The authors note that, for the computation of the spectra calculation programme, the additional filtration is applied at the distance at which the spectra were measured (1 and 2.5 m, respectively) and not right behind the tube window or the filters. Studies have shown though

that the impact of the location of the additional filtration is minute. Therefore, this imprecision does not affect the outcome. The authors also note that the validation method only allows them to confirm the effects of ‘additional’ filtration on the conversion coefficients. Both methods, the simplified model-approach and the X-ray spectra calculation programme, do not facilitate the determination of the effect of ‘missing’ material. However, by considering that the purpose of this work is only to estimate limits for the allowed relative deviation of the mentioned parameters from their recommended values, the assumption of the linearisation of their influence is justified and, therefore, determination of further results with missing material is not required.

RESULTS

High-voltage tube potential

Figure 1 shows that the monoenergetic conversion coefficients follow a smooth curve between the different energies for which they are defined. This allows a linear interpolation between the different values. If a small change in the tube potential is equated with a small change of the energy, it is possible to estimate monoenergetic conversion coefficients for nearby tube potentials.

In the following, this fact is used to estimate the allowed variation of the tube potential such that the monoenergetic conversion coefficients change by 2%. ICRU Report 57 and ICRP Publication 74 indicate ‘monoenergetic’ conversion coefficients, that is, their values are itemised for discrete energies, E_i :

$$h_i = h(E_i). \quad (13)$$

The slope m_i between neighbouring energy values,

$$m_i = \frac{h_{i+1} - h_i}{E_{i+1} - E_i}, \quad (14)$$

relates the ‘absolute’ change in energy with the ‘absolute’ change of the conversion coefficient:

$$\Delta E = \frac{1}{m_i} \cdot \Delta h, \quad (15)$$

where $\Delta E = E_{i+1} - E_i$ and $\Delta h = h_{i+1} - h_i$. This change in energy is related to the ‘relative’ change of the conversion coefficient ($\Delta h/h$) as:

$$\Delta E = \frac{1}{m_i} \cdot (\Delta h/h) \cdot h, \quad (16)$$

where h is defined as the conversion coefficient in the centre of the interval:

$$h = \frac{h_{i+1} + h_i}{2}. \quad (17)$$

The corresponding ‘relative’ change in energy, $\Delta E_{\text{rel}} = (\Delta E/E)$, is, consequently:

$$\Delta E_{\text{rel}} = \frac{1}{m_i} \cdot (\Delta h/h) \cdot \frac{h}{E}, \quad (18)$$

with the corresponding definition of E :

$$E = \frac{E_{i+1} + E_i}{2}. \quad (19)$$

The combination of Equations (17–19) allows the derivation of the necessary relative change in energy resulting in a relative change of the conversion coefficient by 2 %:

$$\Delta E_{\text{rel}} = \frac{E_{i+1} - E_i}{h_{i+1} - h_i} \cdot 0.02 \cdot \frac{h_{i+1} + h_i}{E_{i+1} + E_i}. \quad (20)$$

As mentioned earlier, the relative change in energy, ΔE_{rel} , is equated with the relative change in the high-voltage tube potential, $\Delta E_{\text{rel}} \triangleq \Delta U/U$, and the absolute energy with the photon energy: $E = E_{\text{phot}}$.

Figure 3 shows the relative change in tube potential that leads to a change of the conversion coefficients of 2 % as a function of the photon energy for a phantom definition depth of 10 mm. The 100 %-value is due to the slope of the monoenergetic conversion coefficients being nearly zero around 60 keV (see Figure 1). The solid line denotes the proposed upper limit value.

Figure 4 shows the same for phantom definition depths 3 mm and 0.07 mm. For relative changes larger than ~ 10 %, the approach used is not applicable anymore. Therefore, the proposed limits are restricted to a maximum relative change of 5 %.

The above-mentioned monoenergetic calculations give only estimates of the effect that small changes in

Figure 3. Absolute value of the relative change of the high-voltage tube potential, $|\Delta U/U|$, that results in a relative change of the monoenergetic conversion coefficients of 2 %, as a function of the photon energy, E_{phot} , for phantom definition depth 10 mm. The solid line marks the proposed upper limit values for ISO 4037-1.

the high-voltage tube potential have on the conversion coefficients of real X-ray spectra. This is sufficient for the definition of upper limit values, but to minimise the uncertainty elaborate Monte-Carlo calculations would be required.

Influence of the tube window thickness

According to ISO 4037, the nominal thickness of the tube window (inherent filtration) is either 1-mm beryllium or 4-mm aluminium. This is reflected by the used kerma and dose equivalent spectra given in References (2, 3) to (7). Nowadays, most commercially available X-ray tubes have windows made of beryllium. Therefore, the investigations presented here are confined to influences due to thickness variations of a beryllium window (inherent filtration). As before, the variations that lead to a change of the conversion coefficients of 2 % are obtained.

Figure 5 illustrates the results for $h_{\text{PK}}(10;R;0^\circ)$ and $h_{\text{PK}}(10;R;60^\circ)$ at a distance of 1 and 2.5 m,

Figure 4. Absolute value of the relative change of the high-voltage tube potential, $|\Delta U/U|$, that results in a relative change of the monoenergetic conversion coefficients of 2 %, as a function of the photon energy, E_{phot} , for phantom definition depths 0.07 and 3 mm. The solid and dotted lines mark the proposed upper limit values for ISO 4037-1.

Figure 5. Absolute thickness Δd_{Be} of the additional layer of beryllium in front of the tube window (inherent filtration) that causes a change in $h_{\text{PK}}(10;R;0^\circ)$ and $h_{\text{PK}}(10;R;60^\circ)$ by 2 %.

Figure 6. Absolute thickness Δd_{Be} of the additional layer of beryllium in front of the tube window (inherent filtration) that causes a change in $h_{pK}(3;R;0^\circ)$, $h_{pK}(3;R;60^\circ)$ and $h_{pK}(0.07;R;60^\circ)$ by 2 %.

respectively. Figure 6 shows the same for $h_{pK}(3;R;0^\circ)$, $h_{pK}(3;R;60^\circ)$ and $h_{pK}(0.07;R;60^\circ)$ at 1 m distance. Δd_{Be} denotes the absolute values of the additional beryllium layer.

Influence of the filter thickness

Figure 7 shows the influence of the filter thickness on the value of $h_{pK}(10;R;0^\circ)$ at 1 m distance and $h_{pK}(10;R;60^\circ)$ at 2.5 m distance for the N- and H-series. In cases where a filter is composed of several different layers of material, only one layer is changed at a time.

Figure 8 shows the same for the conversion coefficients $h_{pK}(3;R;0^\circ)$ and $h_{pK}(3;R;60^\circ)$, both in 1 m distance. The influence of the filter thickness on the conversion coefficient is almost irrelevant for phantom definition depth 0.07 mm, since they only depend slightly on the photon energy. To cause a change of 2 %, the relative change $|\Delta d/d|$ has to be $>10\%$ for all radiation qualities. Owing to the manufacturing process, usually, this is automatically satisfied and is not further investigated.

Based on the calculated values that lead to a change of 2 %, upper limit values for the variation of the filter thickness are proposed. They are marked in Figures 7 and 8 as solid and dotted lines.

Influence of filter impurities

The previous investigations show that the conversion coefficient $h_{pK}(10;R;0^\circ)$ at 1 m distance responds most sensitively to changes in the filter thickness. Therefore, the following study concentrates on this condition for the investigation of the influence of filter material impurities. Figure 9 shows the relative surface density of impurities of the filter material, $\rho_{S,impurity}/\rho_{S,all\ filters}$, that causes a change of $h_{pK}(10;R;0^\circ)$ by 2 %. This is determined for different radiation qualities at 1 m distance as a function of the nominal surface density, $\rho_{S,all\ filters}$. The

Figure 7. Absolute value of the relative change of the filter thickness, $|\Delta d/d|$, of a given filter material as a function of the nominal thickness of the filter, d , that results in a relative change of the conversion coefficients $h_{pK}(10;R;0^\circ)$ and $h_{pK}(10;R;60^\circ)$ by 2 %. The solid lines denote the proposed upper limits on the variation of the filter thickness.

Figure 8. Absolute value of the relative change of the filter thickness, $|\Delta d/d|$, of a given filter material as a function of the nominal thickness of the filter, d , that results in a relative change of the conversion coefficients $h_{pK}(3;R;0^\circ)$ and $h_{pK}(3;R;60^\circ)$ by 2 %. The solid lines denote the proposed upper limits on the variation of the filter thickness.

Figure 9. Relative surface density of impurities of the filter material, $\rho_{S,impurity}/\rho_{S,all\ filters}$, that causes a change of $h_{pK}(10;R;0^\circ)$ by 2 % as a function of the nominal surface density of the entire set of filter layers for different radiation qualities.

most common impurities of the corresponding material (typically copper, iron and silicon for aluminium filters) were considered. Owing to the manufacturing process,

large lead impurities [for example, the pure Al-filter at 19.4 g cm^{-2} (H-80)] will not occur in practice and can be excluded from the proposed ISO limit. For filters that consist of various layers, the nominal surface density of the sum of all filter layers has been used. This choice assures that the upper limit values shown in Figure 9 are satisfied, not only by the single layers, but by the entire filter. The dotted lines show the proposed upper limit values for the variation of the filter impurities.

Although the calculations have only been performed for $h_{pK}(10;R;0^\circ)$ at 1 m distance, the proposed upper limit values are also considered to be valid for the definition depths 3 and 0.07 mm.

Uncertainties

The uncertainties of the values for the high-voltage tube potential are believed to be minute. The run of the conversion coefficients curve (as shown in Figure 1) validates the use of a linear interpolation to estimate the resulting conversion coefficients for different high voltages. Linear interpolation has successfully been used in the past for the determination of the (errorless) conversion coefficients listed in Reference (4).

The uncertainties of the values shown in Figures 5–9 are larger the closer the corresponding characteristic energies ($E_{Ka,-1/2}$ and $E_{H,-1/2}$; $E_{Ka,+1/2}$ and $E_{H,+1/2}$) lie together, which define the full-width half-maximum (FWHM) of the kerma and the dose equivalent spectra. From Equations (10) and (11), it can be seen that in the extreme case of the corresponding characteristic energies being identical, no influence of additional layers can be determined using the simplified method. As a consequence, the uncertainties increase with lower phantom definition depth. In other words, the stronger the influence of the investigated parameter is on the conversion coefficient, the smaller the uncertainty of that effect. The smallest uncertainty is estimated to be $\sim 10\%$ ($k = 1$). The largest uncertainty can be as high as one order of magnitude, when the characteristic energies mentioned earlier are almost identical.

All variation values that lead to changes of the conversion coefficients of 2 % and all proposed upper limit values have been checked and confirmed with the validation process described earlier. The empirically determined standard deviation of the estimated 2 %-deviation values is $< 50\%$ for the beryllium window and the filter thickness and reaches a factor of 2 for the filter material impurities. For the selection of upper limit values, these uncertainties were taken into account and the validation study has confirmed that the upper boundary values are conservative.

DISCUSSION

The results of the simplified approximation method are used to derive and propose well-founded upper

limit values on the allowed variations of the crucial parameters for a new revision of ISO 4037 and compare those with the currently valid boundary values. For simplicity, the proposed upper limits are not differentiated between different angles of radiation incidence but are considered to be valid for any angle.

High-voltage tube potential

ISO 4037 sets an upper limit value of 10 % for the maximum allowed variation of the high-voltage tube potential and a maximum allowed deviation of $\pm 1\%$ during operation. Further, a measurement uncertainty of $\leq 2\%$ is demanded. From Figures 3 and 4, it is concluded that notably stricter requirements are necessary. Table 1 summarises upper limit values for $|\Delta U/U|$ that are proposed to be used in the future.

Thickness of the tube window

The thickness of the tube window (inherent filtration) is stated in ISO 4037-1 to be 1-mm beryllium for low photon energies. No uncertainties are given. Based on their results, the authors propose to relax this requirement and allow for variations within the upper limit values given in Table 2.

The stated upper limit values can also be used to determine which radiation qualities of a given X-ray tube are ISO reference fields. As an example, for a 350-kV tube with a 3-mm beryllium window, the listed conversion coefficients of ISO 4037 can be used for N-20, H-40 and higher tube voltages for the phantom definition depth of 10 mm. For radiation qualities with lower tube voltages, the listed conversion coefficients of ISO 4037 cannot be used. For beryllium tube windows thinner than 1 mm, it is necessary to install an additional layer of beryllium such allowing the limits to be satisfied, for example, for H-10 and the phantom definition depth of 3 mm. If this cannot be accomplished, the listed conversion

Table 1. Proposed upper limit values for $|\Delta U/U|$ for a future revision of international standard ISO 4037.

Mean photon energy keV	Upper limit for $ \Delta U/U $ for the definition phantom depth of:		
	10 mm	3 mm	0.07 mm
< 9.5	0.001	0.001	0.02
9.5 to < 14	0.001	0.002	0.02
14 to < 19	0.002	0.005	0.02
19 to < 24	0.005	0.01	0.02
24 to < 35	0.01	0.02	0.02
35 to < 70	0.02	0.02	0.02
≥ 70	0.05	0.05	0.05

Table 2. Proposed new requirements on the thickness of the tube window (inherent filtration) for a future revision of ISO 4037.

Radiation quality	Maximum absolute deviation in millimetre of total inherent filtration, $ \Delta d/Be $, for the definition phantom depth of:		
	10	3	0.07
H-10	0.1	0.1	1
N-10, H-20	0.3	0.3	3
N-15, H-30	0.7	1.5	10
N-20, H-40	2	4	10
N-25, N-30, H-60	10	10	10

coefficients of ISO 4037 cannot be used for the respective photon radiation field.

For high tube voltages (>30 kV for the L- and N-series, >40 kV for the W-series and >60 kV for the H-series), ISO 4037 demands an inherent filtration of a 4-mm aluminium layer. In some (older) X-ray tubes, this might be the tube window itself. Tubes with a beryllium window must have an additional aluminium layer installed. As long as the beryllium tube window is not thicker than 10 mm and there is no other material between the focus point and the window, the attachment of an additional 4-mm layer of aluminium fulfils the proposed adjustment (compare with Figures 5 and 6).

Filter thickness

ISO 4037-1 sets an upper limit value of $\pm 5\%$ on the variation of the filter thickness with respect to the nominal thickness, independent of the composition of the filter. Figures 7 and 8 imply that more specific requirements are reasonable. Especially in the case of thin filters, stricter demands are needed. Table 3 summarises the upper limit values that the authors suggest for filters made solely of aluminium. The authors further propose an upper limit value of 10 % independently of the filter thickness for all other kinds of filters (other materials and composite filters).

Impurities of the filter materials

The maximum allowed impurity as required by ISO 4037-1 is $\leq 0.1\%$, independent of the material and filter thickness. The impurity in this case is considered as the surface density of the impurity, $\rho_{S, \text{impurity}}$, divided by the surface density of the filter material, $\rho_{S, \text{filter}}$. According to Figure 9, it is appropriate to relax these requirements drastically. This holds for aluminium filters when the impurities are common metals (copper, silicon and iron), but not for lead or

Table 3. Proposed upper limit values for $|\Delta d/d|$ for filters made of aluminium for a new revision of ISO 4037.

Al filter thickness mm	Upper limit for $ \Delta d/d $ for the definition phantom depth of:		
	10 mm	3 mm	0.07 mm
<0.8	0.02	0.04	0.1
0.8 to <1.5	0.03	0.04	0.1
≥ 1.5	0.04	0.07	0.1

Table 4. Proposed upper limit values for the relative impurity of filter materials, denoted as surface density ratio, $\rho_{S, \text{impurity}}/\rho_{S, \text{filter}}$ for a new revision of ISO 4037.

$\rho_{S, \text{filter}}$ g cm ⁻²	Upper limit for $\rho_{S, \text{impurity}}/\rho_{S, \text{filter}}$ for filtration of:		Remark
	Only Al	Mixed metals	
<3	0.003	0.01	For Al filters the limit for heavy metals is 0.001
3 to <20	0.005	0.01	
≥ 20	0.01	0.05	

other heavy metals. However, this is not a problem because, due to the manufacturing process, heavy metal impurities in aluminium occur only very rarely. Furthermore, the requirements can be lowered for filters made of tin and lead.

It is not required to perform further studies on the dependency of the phantom definition depth. As the investigations were made for a definition depth of 10 mm, the proposed upper limit values automatically hold for the 3 and 0.07 mm as well. Table 4 summarises the proposed upper limit values shown in Figure 9.

CONCLUSION

This work investigates the implications that variations of the relevant parameters for the creation of photon reference fields with X-ray tubes have on the resulting conversion coefficients. These relevant parameters are the high-voltage tube potential, thickness and impurities of the filters and thickness of the tube window. A simplified mathematical model is used to estimate the necessary variations that lead to a change of the conversion coefficients by 2 %. The resulting values illustrate that the demands on the relevant parameters for the creation of photon reference fields as stated by the first part of ISO 4037 are not properly adjusted to the corresponding phantom-related quantities. In particular, the requirements on the tube's high voltage and the filter thickness have to be more stringent. In contrast to what was done in the past, the authors

also propose to set differentiated demands on different types of filters, taking into account the absolute thickness and composition of the filters. For the beryllium window of the X-ray tube, no maximum allowed variations were given so far. The authors suggest the incorporation of the above-stated upper limits in a future revision of ISO 4037. The simplified mathematical model used for the calculations is validated using an X-ray spectra calculation programme. Although the estimates made with the simplified mathematical model show large uncertainties, the proposed upper limit values were chosen taking these uncertainties into account and validation studies have shown that these values are conservative.

It is desirable in the future to perform more elaborate Monte-Carlo simulations of the entire X-ray tube to obtain deeper knowledge of the impact of different tube parameters on the created photon reference field.

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