A radiation quality correction factor $k_Q$ for well-type ionization chambers for the measurement of the reference air kerma rate of $^{60}$Co HDR brachytherapy sources

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**Purpose:** The aim of this study was to investigate whether a chamber-type-specific radiation quality correction factor $k_Q$ can be determined in order to measure the reference air kerma rate of $^{60}$Co high-dose-rate (HDR) brachytherapy sources with acceptable uncertainty by means of a well-type ionization chamber calibrated for $^{192}$Ir HDR sources.

**Methods:** The calibration coefficients of 35 well-type ionization chambers of two different chamber types for radiation fields of $^{60}$Co and $^{192}$Ir HDR brachytherapy sources were determined experimentally. A radiation quality correction factor $k_Q$ was determined as the ratio of the calibration coefficients for $^{60}$Co and $^{192}$Ir. The dependence on chamber-to-chamber variations, source-to-source variations, and source strength was investigated.

**Results:** For the PTW Tx:33004 (Nucletron source dosimetry system (SDS)) well-type chamber, the type-specific radiation quality correction factor $k_Q$ is 1.19. Note that this value is valid for chambers with the serial number, SN ≥ 315 (Nucletron SDS SN ≥ 548) onward only. For the Standard Imaging HDR 1000 Plus well-type chambers, the type-specific correction factor $k_Q$ is 1.05. Both $k_Q$ values are independent of the source strengths in the complete clinically relevant range. The relative expanded uncertainty ($k = 2$) of $k_Q$ is $U_{k_Q} = 2.1\%$ for both chamber types.

**Conclusions:** The calibration coefficient of a well-type chamber for radiation fields of $^{60}$Co HDR brachytherapy sources can be calculated from a given calibration coefficient for $^{192}$Ir radiation by using a chamber-type-specific radiation quality correction factor $k_Q$. However, the uncertainty of a $^{60}$Co calibration coefficient calculated via $k_Q$ is at least twice as large as that for a direct calibration with a $^{60}$Co source.

**Key words:** HDR brachytherapy sources, well-type ionization chamber, high dose rate cobalt-60 sources, high dose rate iridium-192 sources, source calibration

1. INTRODUCTION

More than 10 years ago, a miniaturized $^{60}$Co high-dose-rate (HDR) brachytherapy source with geometrical dimensions similar to the commonly used $^{192}$Ir HDR sources was introduced into the clinics. Because of the long half-life of $^{60}$Co ($t_{1/2} = 1924$ days), afterloader systems based on $^{60}$Co require a source replacement every 5 years at the most, while systems based on $^{192}$Ir ($t_{1/2} = 73.8$ days) require a replacement at least every 4 months. In particular for hospitals in developing countries, the source exchange frequency is a crucial factor due to the lack of the required infrastructure for the transport of highly radioactive sources and the efforts required for customs clearance which can take a long time compared to the half-life of $^{192}$Ir. Delays during the transportation of $^{60}$Co sources are less critical. The relatively small differences in the radial dose distribution of $^{60}$Co sources compared to $^{192}$Ir sources do not result in clinically significant effects. Different companies provide $^{60}$Co HDR brachytherapy sources and at least 200 remote afterloader systems equipped with $^{60}$Co are presently in operation worldwide.

The dosimetric verification of a $^{60}$Co brachytherapy source in a hospital using an in-air experimental set-up is complex and time-consuming and may be error-prone, among other things, due to lack of guidelines for $^{60}$Co sources in the existing dosimetry protocols. For the commonly used radionuclides, well-type ionization chambers are well established for routine calibrations of brachytherapy sources. Using a well-type chamber there is no need for accurate source-to-detector distance measurement and owing to its large detection volume, the ionization current is high and thus easy to measure with high precision. For $^{192}$Ir HDR brachytherapy sources the traceability to a national standard is provided by several national metrology institutes (NMIs), whereas in the case of $^{60}$Co only the German NMI—the Physikalisch-Technische Bundesanstalt (PTB)—offers a calibration service. In this work, an investigation was performed to find out whether a chamber type-specific radiation quality correction factor $k_Q$ can be determined in order to enable the measurement of the reference air kerma rate (RAKR) of a $^{60}$Co HDR brachytherapy source with acceptable uncertainty by means of a well-type ionization chamber calibrated for $^{192}$Ir HDR sources.

The following procedure was used. First, the determination of the RAKR of $^{60}$Co and $^{192}$Ir brachytherapy sources was carried out with the PTB calibration facility for HDR brachy-
therapy sources (Sec. 2.C). Subsequently, for each of 35 well-type chambers under study the calibration coefficients $N_{Ir-192}$ and $N_{Co-60}$ for radiation fields of $^{192}$Ir and $^{60}$Co were determined (Sec. 2.D). The range of source strengths and the influence of source-to-source variations on the calibration coefficients were investigated (Secs. 3.A and 3.B), respectively. Finally, the radiation quality correction factor $k_Q = N_{Co-60}/N_{Ir-192}$ was analyzed with respect to chamber-to-chamber variations (Sec. 3.C), and a detailed uncertainty analysis is presented (Sec. 3.D).

2. MATERIALS AND METHODS

2.A. Well-type ionization chambers

In order to analyze the chamber-to-chamber variations, a large number of chambers of two different types were studied: nine chambers of the type HDR 1000 Plus from Standard Imaging (Standard Imaging Inc., Middleton, WI) with the source holder insert REF 70110 named “Bebig Co-60 and Ir-192 Afterloader Source Holder,” and 26 chambers of the type Tx33004 from PTW (PTW-Freiburg, Freiburg, Germany) in connection with the source holder insert T33002.1.009 named “Adapter for Nucletron microSelectron afterloaders.” The latter chamber type is distributed by Nucletron/Elektro (Nucletron B.V., Veenendaal, The Netherlands; Nucletron is now a member of the Elekta group of companies) as “Source Dosimetry System—SDS” under reference number 077.094 for the member of the Elekta group of companies) as “Source Dosimetry System—SDS” under reference number 077.094 for the Elekta (Nucletron) T33004 Triax TNC 077.091 and Nucletron T33004 Triax BNT 077.092 manufactured with different electrical connectors indicated by $x = M, W, \text{or } N$ as listed in Table I. TM33004 chambers have the collecting electrode and the guard at ground potential, whereas for TW33004 and TN33004 chambers the collecting electrode and the guard are connected to high voltage. Douysset et al.\textsuperscript{27} pointed out that there is an undesired collection volume, located in the region between the base plate of the chamber enclosure and the electrical terminal of the collecting electrode. For chambers of type $x = W$ and $N$, about 1% of the total measured signal may originate from ionization in this region, whereas for the $x = M$ model there is no evidence of a significant extra collecting volume.\textsuperscript{27} A possible effect on the calibration coefficient was investigated as described below in Sec. 3.A.

The nine HDR 1000 Plus chambers under test all have the same connecting system (Triax BNC or TNC).

2.B. HDR brachytherapy sources

In order to analyze the influence of source variations, several exemplars of different source types have been measured in this study: a $^{60}$Co HDR source of type “Flexi-source Co-60”\textsuperscript{10} provided by Nucletron/Elektro under reference number 136.002, and three $^{60}$Co sources of type Co0.A86 (Ref. 9) provided by Bebig (Eckert & Ziegler Bebig GmbH, Berlin, Germany), hereinafter referred to as Bebig Co-60. In order to investigate the influence of the source strength on the calibration coefficient, a source with an apparent activity of about 75 GBq and another one with an apparent activity of about 35 GBq were used. This covers more than the clinically relevant range of source strengths between the source replacements (74–37 GBq). Both $^{60}$Co source types have a similar design, in particular the geometric dimensions of the radioactive component are identical\textsuperscript{28} (see Table II).

The surveyed $^{192}$Ir source types are: microSelectron HDR classic and microSelectron V2, both manufactured on behalf of Nucletron by Mallinckrodt Medical (Mallinckrodt Medical B.V., Petten, The Netherlands) as well as GammaMed 232 (for GammaMed Plus afterloaders) distributed by NTP (NTP Radioisotopes S.A., Fleurus, Belgium). Using a single microSelectron V2 source with an initial apparent activity of about 470 GBq, the measurements were repeated several times during approximately three half-life periods. This covers more than the clinically relevant range of source strengths between the source replacements (370–185 GBq). All three $^{192}$Ir source types have a similar design with a slightly different radioactive component (see Table II). Influences on the chamber calibration coefficient were investigated as described below in Sec. 3.B.

2.C. Determination of the RAKR of HDR brachytherapy sources

The RAKR $K_R$ is the measurement quantity for specifying the strength of a brachytherapy gamma-emitting source recommended by the International Commission on Radiation Units and Measurements (ICRU).\textsuperscript{14,29–31} The numerical values of the RAKR and of the equivalent but dimensionally different quantity air kerma strength $S_K$ are identical.\textsuperscript{20,21} PTB has been offering calibrations of HDR brachytherapy sources in terms of RAKR for several years.\textsuperscript{32} A photograph of the calibration facility at PTB is shown in Fig. 1. The HDR source to be calibrated is placed by means of a custom-built afterloading system (A) several mm beyond the open tip of a catheter needle in the center of a lead collimator (B) (collimator opening

| Capsule | Active component | $D$ | $L$ |
|---------|------------------|-----|-----|
| Bebig Co-60 | 1.0 | 0.5 | 3.5 |
| Flexisource Co-60 | 0.9 | 4.3 | 0.5 | 3.5 |
| microSelectron HDR classic | 1.10 | 8.00 | 0.60 | 3.50 |
| microSelectron V2 | 0.90 | 4.50 | 0.65 | 3.60 |
| GammaMed 232 | 0.9 | 4.57 | 0.6 | 3.5 |

Table II. Diameter $D$ in mm and length $L$ in mm of active component and encapsulation of the sources as specified in source certificates from each manufacturer.
In-air experimental set-up at PTB for determination of the reference air kerma rate of HDR brachytherapy sources. (A) Custom-built afterloading system. (B) Lead housing with collimator opening. (C) Commercially available industrial robot. (D) Secondary standard ionization chamber of type LS01 (PTW TM32002 SN:0302).

5.5 cm in diameter). By use of this set-up for realizing a collimated radiation field, the back-scattered radiation from walls and air is reduced from about 5% with an uncollimated 192Ir source to (0.5 ± 0.5)% with the used special collimation. By means of a commercially available industrial robot (C), a secondary standard ionization chamber (D) is positioned— with a positioning accuracy better than 0.1 mm—along the central axis of the radiation field which is perpendicular to the cylindrical axis of the source with an intersection at the source center. The secondary standard chamber is of the type LS01 (PTW TM32002 SN:0302) with a spherical shape and an active volume of 1000 cm³. The ionization current of the chamber is measured using a calibrated electrometer type Keithley 6517 in integrated mode.

In order to reduce the uncertainty in the positioning of the radiation source (<2 mm) and, therefore, in the measuring distance between source and chamber, measurements are carried out at five different distances d in the range of d = 80–160 cm. By applying the inverse square law, the offset d_{off} is obtained from the axis intercept of a linear fit to the inverse square root of the ionization current, which is corrected for the contributions from scattered radiation and air attenuation. In this way, the uncertainty of the source-to-chamber distance is reduced to less than 0.4 mm.

In order to consider radial anisotropy of the radiation field of the source, the azimuthal angle of the source with respect to the chamber was varied: measurement series are repeated several times after arbitrary axial rotation of the source wire. Thus, differences due to radial anisotropy of the source are likely to average out. The radial anisotropy of each source was determined in a separate experimental set-up and was found to be less than 0.3% peak-to-peak variation in each case.

The RAKR at reference time t₀ is given by

\[ K_{R}(t_0) = N_R^{LS01} \cdot I \cdot k_{TP} \cdot k_{att} \cdot k_{sc} \cdot k_{dec} \left( \frac{d - d_{off}}{d_{ref}} \right)^2, \]  

where \( N_R^{LS01} \) is the calibration coefficient of the LS01 chamber for 60Co or 192Ir radiation, I is the measured ionization current, \( k_{TP} = \rho_d T / \rho_0 T_0 \) is the correction factor for the deviation of the air density from reference conditions \( (T_0 = 293.15 \text{ K and } p_0 = 1013.25 \text{ hPa}) \), \( k_{att} \) corrects the attenuation of the radiation by the air between source and chamber, \( k_{sc} \) is the correction factor due to scattered radiation from surroundings and scattering in the air, \( k_{dec} \) considers the radioactive decay between measurement time and reference time \( t_0 \), \( d \) is the distance between the source and the middle of the spherical volume of the chamber corrected for the offset \( d_{off} \), and \( d_{ref} \) is the reference distance which is specified as \( d_{ref} = 1 \text{ m} \) in the RAKR definition.

The calibration coefficient \( N_R^{LS01} \) for 60Co is derived by traceable calibration of the LS01 secondary standard chamber in a 60Co reference field to a custom-built graphite walled cavity ionization chamber referred to as HRK-3.33,34 The HRK-3 is one of PTB’s primary standards for air kerma free in air for 60Co and 192Ir gamma radiation35,36 based on the Bragg-Gray cavity theory.

The calibration coefficient \( N_R^{192Ir} \) for 192Ir was derived from an interpolation method,17,37 where the response of the chamber for 137Cs and 60Co radiation as well as for ten different x-ray qualities at tube voltages in the range from 10 to 300 kV was measured.36 A determination of the RAKR of the same 192Ir source with the HRK-3 primary standard chamber and with the LS01 chamber agrees within 0.5%, within the estimated uncertainties.36 Due to the low ionization current owing to the small dimensions of the HRK-3 chamber, the large-volume LS01 secondary standard chamber is used for routine calibrations.

The correction factors in Eq. (1) for the remaining scattered radiation from the collimator, air, and walls \( k_{sc}(d) \) and for the attenuation of the primary radiation by air \( k_{att}(d) \) are determined by MC calculations on the one hand and by experimental determination of \( k_{att}(d) \) applying the shadow shield method32,37 and calculation of \( k_{att}(d) \) from mass attenuation coefficient of dry air38 on the other hand. The results of both procedures agree within 0.7%. The combined correction factor for attenuation and scattering \( k_{att}(d) \cdot k_{sc}(d) \) from mass attenuation coefficient of dry air is typically 0.975 for 60Co and 1.01 for 192Ir (for \( d = 1 \text{ m} \)). Effects of the finite size of the spherical ionization chamber in a radiation field of a point-like source39 are negligibly small (<0.1%).

2. D. Calibration of well-type chambers for 192Ir and 60Co HDR brachytherapy sources

Well-type chambers are used in combination with a replaceable source holder insert (also called an applicator adaptor) with a guide tube to hold the afterloader catheter, the applicator needle, or the source directly on the axis of the cylindrical well. The response of the chamber versus the source position along the guide tube has a maximum. The calibration coefficient of a well-type chamber is only valid if the source to be calibrated is positioned at this point.

The position of maximum response is determined during each calibration measurement by shifting the calibration source by means of the afterloader system in steps of about 2 mm from the bottom limit stop of the source holder insert.
Fig. 2. Normalized ionization current \( I/I_{\text{max}} \) of a TM33004 well-type chamber as a function of source position \( p \) with respect to the point of maximum current for \( ^{60}\text{Co} \). Full (blue) circles: \( ^{60}\text{Co} \) source. Well-type chamber “free in air,” i.e., with \( >1 \text{ m} \) distance from walls and floor. Open (red) squares: same, but for \( ^{192}\text{Ir} \) source instead of \( ^{60}\text{Co} \). Open (gray) diamonds: same, except for chamber that is enclosed by a radiation shield of lead bricks. Normalization to maximum current without lead shield. Curves: parabola fits.

to the top. The position of maximum response depends on the source type, as becomes apparent in Fig. 2 by the comparison of the measured ionization currents versus the source position of an \( ^{192}\text{Ir} \) source (open red squares) and a \( ^{60}\text{Co} \) source (full blue circles).

The calibration coefficient \( N_R \) of a well-type chamber in terms of RAKR is determined from

\[
N_R = \frac{\tilde{K}_R(t_0)}{(I_{\text{max}} - I_{\text{leak}}) \cdot k_{T\text{p}} \cdot k_{\text{ion}} \cdot k_{\text{dec}} \cdot k_{\text{ins}}}.
\]

(2)

where \( \tilde{K}_R(t_0) \) is the RAKR of the source at reference time \( t_0 \), \( I_{\text{max}} \) is the measured ionization current at the source at the point of maximum response, \( I_{\text{leak}} \) takes into account the leakage current, and the correction factors are: \( k_{\text{ion}} \) for recombination losses, \( k_{T\text{p}} = p_0 T_p/p_0 T_0 \) for deviation of air density from reference conditions \( (T_0 = 293.15 \text{ K} \) and \( p_0 = 1013.25 \text{ hPa}) \), \( k_{\text{dec}} \) for radioactive decay between the time of chamber calibration measurement and reference time \( t_0 \), and \( k_{\text{ins}} \) takes into account differences between source holder inserts.

The well-type chamber to be calibrated is placed in the room “free in air,” i.e., in a minimum scatter environment, with a distance >1 m from walls and floor as recommended.\(^{30}\) Using a well-type chamber in the vicinity of a concrete wall can increase the ionization current from \( ^{192}\text{Ir} \) by up to 1.1%.\(^{40}\) Due to radiation protection purposes for some measurements with \( ^{60}\text{Co} \), the well-type chamber was placed inside a shield of lead which results in deviations of \( I_{\text{max}} \) of only about 0.2% (open gray diamonds in Fig. 2).

All surveyed chambers exhibited a negligible leakage current \( I_{\text{leak}} \) with a maximum value of 50 fA. For the calculation of \( k_{T\text{p}} \), a temperature sensor is placed in contact with the outside wall of the chamber. The chambers were positioned in the measuring room the day before the calibration measurement in order to achieve equilibrium with the room temperature.

The correction factor for a different source holder type is given by \( k_{\text{ins}} = N_R^x = N_R^{\text{ins}}/N_R^{\text{ref}} \), where \( N_R^{\text{ref}} \) is the calibration coefficient for using the source holder type which serves as a reference in this work, i.e., T33002.1.009 for Tx33004 chambers and REF 70110 for HDR 1000 Plus chambers, and \( N_R^{\text{ins}} \) is the calibration coefficient for using a different source holder type. Experimentally determined \( k_{\text{ins}} \) values for some different source holder types are given in Table III. Note that \( k_{\text{ins}} \) is different for \( ^{60}\text{Co} \) and \( ^{192}\text{Ir} \). Hence, the use of a different source holder type must be taken into account for the application of \( k_Q \). The standard source holder for HDR 1000 Plus chambers for HDR \( ^{192}\text{Ir} \) sources (REF 70010) differs from the used “Bebig Co-60 and Ir-192 Afterloader Source Holder” (REF 70110) only in the diameter of the inner tube. Both tubes are made from the same alloy and have the same wall thickness,\(^{41}\) so there are no significant differences and \( k_{\text{ins}} = 1 \) for REF 70010 as well as for REF 70110.

The amount of ion recombination losses in the chamber volume depends on the chamber bias voltage, the source strength, and the radiation quality, i.e., the nuclide. The incomplete saturation due to ion recombination is taken into account by the correction factor \( k_{\text{ion}} = 1/A_{\text{ion}} = I_{\text{sat}}/I_1 \), where \( I_{\text{sat}} \) is the saturation current and \( I_1 \) the measured current at chamber bias voltage \( U_1 \) used for calibration. \( A_{\text{ion}} \) is the ion collection efficiency. \( I_{\text{sat}} \) is determined by recording the ionization current \( I \) as a function of chamber bias voltage \( U \) and subsequent extrapolation of \( I \) for \( U \to \infty \). For continuous radiation and if volume recombination is the predominant process, a plot of \( 1/I \) versus \( 1/U^2 \) reveals a straight line with axial intercept of \( 1/I_{\text{sat}} \).\(^{42}\) For ideal conditions, it is sufficient to carry out the extrapolation on the basis of only two data points by using the so-called two-voltage technique formula\(^{30,43}\)

\[
A_{\text{ion}} = \frac{4}{3} - \frac{I_1}{3I_2} = \frac{1}{k_{\text{ion}}} = \frac{I_1}{I_{\text{sat}}},
\]

(3)

where \( I_1 \) is the ionization current at chamber bias voltage \( U_1 \) and \( I_2 \) is the current at \( U_1/2 \).

Figure 3(a) shows a plot of \( 1/I \) versus \( 1/U^2 \) normalized to \( 1/I_{\text{sat}} \) calculated from Eq. (3) for a TM33004 chamber with a \( ^{60}\text{Co} \) source. There are only marginal deviations from the linear fit and axial intercept from unity. HDR 1000 Plus chambers show such linear dependence too. However, Tx33004 cham-

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**Table III.** Correction factor \( k_{\text{ins}} \) for the use of different source holder inserts. Uncertainty is 0.2%.

| Source holder insert | \( k_{\text{Co-60}}^{\text{ins}} \) | \( k_{\text{Ir-192}}^{\text{ins}} \) |
|----------------------|-------------------------------|-------------------------------|
| T33002.1.009         | 1                             | 1                             |
| T33004.1.011         | 1.024                         | 1.019                         |
| T33004.1.012         | 1.027                         | 1.029                         |
| Only steel needle\(^a\) | 0.976                         | 0.986                         |
| REF 70110 or REF 70010 | 1                             | 1                             |
| Only steel needle\(^c\) | 1.017                         | 0.997                         |

\(^a\)E&Z Bebig LAA1400-RU \( \approx 3 \text{ mm} \).

\(^b\)Varian GM11002070 \( \approx 3 \text{ mm} \).

\(^c\)E&Z Bebig LLA200-S \( \approx 1.7 \text{ mm} \).

\(^d\)Varian GM11003350 \( \approx 1.65 \text{ mm} \).
Determination of saturation current $I_{\text{sat}}$ of $^{60}$Co sources with an apparent activity of about 73 GBq by recording ionization current $I$ as a function of chamber bias voltage $U$. (a) Chamber model $x=M$: linear extrapolation of $1/I$ vs $1/U^2$. (b) Chamber model $x=W$: linear extrapolation of $1/I$ vs $1/U$. Normalization with respect to $1/I_{\text{sat}}$ calculated with Eq. (3).

$A_{\text{ion}} = 2 - I_1/I_2 = I_1/I_{\text{sat}}$.

Note that $^{60}$Co sources with different apparent activities. Saturation current $I_{\text{sat}}$ calculated by Eq. (3) for $x=M$ chambers and by Eq. (4) for $x=W$ chambers. For $x=M$ chambers (open symbols), deviations of about 0.3% due to incomplete saturation are observed also for $U=U_1=400$ V. However, the neglect of the incomplete saturation by setting $k_{\text{ion}}=1$ results in differences between strong and weak sources of <0.2%.

Fig. 4 shows the saturation curves of the PTW $^{60}$Co chambers for $^{60}$Co HDR sources with apparent activities of 33 and 73 GBq. Even for bias voltages of $U > 250$ V, saturation is achieved, i.e., $A_{\text{ion}} > 99.99\%$, also for apparent activities >400 GBq. Thus $k_{\text{ion}}$ can be set to 1 in the complete clinically relevant range of source strengths. For chambers of the type $x=M$, deviations are obvious here too, but differences between strong and weak sources are negligible (<0.1%).

3. RESULTS

The radiation quality correction factor $k_Q = N_{\text{Co-60}}/N_{\text{Ir-192}}$ was derived and the dependence on chamber-to-chamber variations, source-to-source variations, and source strength was investigated as described in the following.

3.A. Range of source strength

Fig. 4 shows saturation curves, i.e., the ionization current $I$ normalized to $I_{\text{sat}}$ as a function of bias potential $U$, of different PTW $^{60}$Co HDR sources with different apparent activities. Saturation current $I_{\text{sat}}$ is calculated by Eq. (3) for $x=M$ chambers and by Eq. (4) for $x=W$ chambers. For $x=M$ chambers (open symbols), the saturation curves show only marginal deviations for sources with the same apparent activities. Thus, the ion collection efficiency is nearly the same for all chambers of this type.
Similar results are obtained with HDR 1000 Plus well-type chambers. Figures 6 and 7 show the saturation curves of different HDR 1000 Plus chambers for $^{192}$Ir and $^{60}$Co HDR sources, respectively. The saturation curves are nearly the same for similar apparent activities, so ion collection efficiency $A_{\text{ion}}$ is a chamber-type specific value. Even for the strong sources with apparent activities at the upper limit of the clinically relevant range, $A_{\text{ion}}$ is larger than 99.9% (for $U = U_1 = 300$ V). Differences between strong and weak sources are negligible (<0.1%) and $k_{\text{sat}}$ can be set to 1.

Douysset et al. (Ref. 27) have observed for a well-type chamber of type TW33004 a decrease of about 0.6% in the $^{192}$Ir calibration coefficient upon the decrease of the source strength of the calibration source after some half-life periods. In order to investigate this effect, the calibration of eight TM33004 well-type chambers was repeated with the same $^{192}$Ir source at different measuring times during approximately three half-life periods for apparent activities between about 470 GBq and about 60 GBq. This range of source strengths covers more than the clinically relevant range between the source replacements. Figure 8 shows the normalized calibration coefficients determined for different source strengths of the $^{192}$Ir source (open blue symbols). The normalization is performed on the average of all calibration coefficients $N(K_R)$ of each chamber $i$. The calibration coefficients agree within ±0.05%. Thus, within the studied range of source strengths the calibration coefficient does not show any dependence on the source strength.

In contrast, the data of Douysset et al. (Ref. 20, 27) for a TW33004 well-type chamber (Nucletron 077.091, SN 25324) exhibit a decrease of about 0.6% (small joined symbols in Fig. 8). This may be an effect of an erroneous recombination correction for $x = W$ chambers by using Eq. (3) instead of Eq. (4).

The $^{60}$Co calibration coefficient is also unaffected by the source strength: the eight TM33004 chambers were calibrated with a $^{60}$Co source with an apparent activity of 75 GBq as with an additional source with an apparent activity of about 34 GBq. Thereby, both limits of the clinically relevant range between the source replacements are reached. As shown in Fig. 8, the normalized calibration coefficients agree within ±0.05% (full red symbols).

Since the calibration coefficients for both $^{60}$Co and $^{192}$Ir are independent of the source strength within the clinically relevant range of source strengths, $k_\Omega$ is independent as well.

3.B. Source-to-source variation

The length of the active part of a source and also the shape and thickness of its encapsulation differ between the different
source types (see Table II) and may vary slightly from source to source due to manufacturing tolerances. In particular for $^{192}$Ir, the self-absorption of photons along the source axis is considerable. Thus, the photon fluence is a function of the angle with respect to the source axis (polar angle). According to the RAKR definition, this anisotropy is not taken into account for source calibrations. However, well-type ionization chambers are sensitive to almost $4\pi$ and, thus, differences in the polar anisotropy from one source to another might have an effect on the induced ionization current and the calibration coefficient of the chamber.

Figure 9 shows for the same well-type chamber the deviations $\Delta N_{R}(j) = N_{R}(j)/N_{R}(j) - 1$ of the calibration coefficient $N_{R}(j)$ of different sources $j$ from their mean value $N_{R}(j)$ for $^{192}$Ir and $^{60}$Co, respectively. Both chamber types—TM33004 (open symbols) and HDR 1000 Plus (full symbols)—reveal similar deviations for the same source. The differences between the three $^{192}$Ir source types can be neglected compared to the individual differences due to manufacturing tolerances and to the uncertainty of the source calibration procedure. The standard deviation is about $\pm 0.3\%$. The expanded uncertainty ($k = 2$) of the mean value of the 18 sources is 0.14%. In the case of $^{60}$Co sources, differences in absorption by the source components due to manufacturing tolerances have less influence owing to the higher photon energy. The maximum deviations are less than $\pm 0.2\%$ (diamonds).

The sources with number $j = 10$ and 11 are used for the measurement of the individual $^{192}$Ir calibration coefficients $N_{R,192}(j)$ of the 35 well-type chambers $i$. The deviations from the mean calibration coefficient for these sources are at least $-0.2\%$ and $+0.2\%$, respectively. In order to determine a source-to-source variation independent $k_{Q}$ value, these deviations are corrected to match the mean calibration coefficient $N_{R,192}(j)$.

3.C. Chamber-to-chamber variation

The individual calibration coefficients $N_{Co-60}(i)$ and $N_{Ir-192}(j)(i)$ were determined for a large number of chambers $i$. The individual radiation quality correction factors $k_{Q}(i) = N_{Co-60}(i)/N_{Ir-192}(j)(i)$ are analyzed with respect to chamber-to-chamber variances due to manufacturing tolerances.

Figure 10 shows the individual radiation quality correction factors $k_{Q}(i)$ of 26 PTW Tx33004 well-type ionization chambers in connection with a T33002.1.009 source holder as a function of the serial number (SN) of the chamber. In order to uncover the chamber-to-chamber variances, the error bars do not include the contribution due to the systematic uncertainties of the RAKR of the sources, which are the same for all chamber calibrations. For the same chamber, the $k_{Q}(i)$ values obtained with the Bebig Co-60 sources (full circles) and of the Flexisource Co-60 (open squares) agree within their uncertainties.

Chambers with higher SN feature $k_{Q}(i)$ values which agree within $\pm 0.4\%$, whereas chambers with a lower SN differ by up to about 3%. At the request of PTB, the manufacturer PTW states that well-type chambers of the type Tx33004 (and Nucletron SDS) are manufactured by identical methods and with significantly smaller tolerances due to improved machinery and improved manufacturing methods, from serial number 315 (and Nucletron SDS serial number 548) onward.44 Chambers built before 2009 with PTW SN < 315, Nucletron SDS SN < 548, as well as with the obsolete Nucletron serial number 25xxx (left of dashed vertical line in Fig. 10) may differ from up-to-date chambers. The chamber-type-specific radiation quality correction factor is derived from the average over the individual correction factors of all investigated chambers with SN > 315 to $k_{Q} = k_{Q}(i) = 1.190$ (continuous horizontal line in Fig. 10).
The determined $^{60}\text{Co}$ calibration coefficients differ from the manufacturer’s data by more than 2%, as the radiation quality correction factor currently used by PTW was derived from measurements using older chambers with SN < 315. The uncertainty of the $^{60}\text{Co}$ calibration coefficient stated in the manufacturer’s data is 3%.

Figure 11 shows the individual radiation quality correction factors $k_Q(i)$ (i.e., chamber serial number) for HDR 1000 Plus well-type chambers with widely spread serial numbers (manufacturing dates between 2001 and 2011) in combination with source holder REF 70110. All values agree within ±0.3%. The type-specific radiation quality correction factor is derived from the average over the individual correction factors to $k_Q = k_Q(i) = 1.050$ (continuous horizontal line in Fig. 11). The manufacturer Standard Imaging states that well-type chambers of the type HDR 1000 Plus have not undergone any significant technical changes since their release in 1998 and source holder inserts REF 70010 and REF 70110 have been built without changes over the years.41

The determined $^{192}\text{Ir}$ calibration coefficients $N_{kQ,192}$ of all studied HDR 1000 Plus chambers and $^{103}\text{Pd}$ chambers with SN > 315 show only small chamber-to-chamber variations (maximal 1.5% difference). The approximation by a linear relationship between $N_{kQ,192}$ and the $^{60}\text{Co}$ calibration coefficient $N_{Co,60}$ is suitable as obvious in Fig. 12. A deviation of $N_{kQ,192}$ of more than 2% from the typical value of 0.468 (mGy/h)/nA (for HDR 1000 Plus) or 0.972 (mGy/h)/nA (for $^{103}\text{Pd}$), respectively, is an indication of an abnormal chamber with possible deviations from the linear relationship as observed for $^{103}\text{Pd}$ chambers with SN < 315. In this case, a direct calibration with a $^{60}\text{Co}$ source is advisable and the quality correction factor should not be applied for the calculation of a $^{60}\text{Co}$ calibration coefficient. Table IV summarizes the results of the determined type-specific radiation quality correction factors $k_Q$ and specifies the range within a calibration coefficient $N_{kQ,192}$ of a chamber must be for the application of $k_Q$.

The significant difference of the $k_Q$ values (14%) between the two chamber types probably originates from the different response for photons from the low-energy fraction of the spectral fluence of $^{192}\text{Ir}$. The HDR 1000 Plus chamber can be used for measuring the RAKR of low-energy photon emitting brachytherapy sources like $^{125}\text{I}$ or $^{103}\text{Pd}$ whereas the $^{103}\text{Pd}$ chamber is not suitable for this purpose. There is a new well-type chamber from PTW called Sourcecheck for $^{103}\text{Pd}$ which can be used for $^{125}\text{I}$ as well. The ratio of the calibration coefficients for $^{60}\text{Co}$ and $^{192}\text{Ir}$ of one chamber of this type measured up to now is clearly smaller than the $k_Q$ value for $^{103}\text{Pd}$ chambers. The determination of the type-specific radiation quality correction factor $k_Q$ from measurements with several additional Sourcecheck chambers is currently in preparation.

### 3.D. Uncertainties

For both chamber types, the contribution to the uncertainty of $k_Q$ due to chamber-to-chamber variations is less than 0.4%.

### Table IV. Results for the type-specific radiation quality correction factor $k_Q$

| Chamber   | Source holder | $k_Q$ | $N_{kQ,192}$ (mGy/h)/nA |
|-----------|---------------|------|--------------------------|
| HDR 1000+ | REF 70010 or REF 70110 | 1.050 | 0.462–0.474 |
| $^{103}\text{Pd}$ | T33002.1.009 | 1.190 | 0.960–0.984 |
| $^{103}\text{Pd}$ | T33002.1.011 | 1.196 | 0.978–1.003 |
| $^{103}\text{Pd}$ | .012 or .013 | 1.050 | 0.462–0.474 |

*Nucletron type 077.095.*

*Nucletron SDS: SN > 548.*
This is small compared to the uncertainties for the determination of the RAKR of $^{192}$Ir (1.5%, $k = 2$) and $^{60}$Co (1.3%, $k = 2$) sources. The expanded uncertainty of $k_Q$ was determined according to the GUM (Ref. 45) and is $U(k_Q) = 2.1\%$ ($k = 2$) for both chamber types. The uncertainty components are listed in Table V.

4. SUMMARY

Well-type ionization chambers are well suited as a secondary standard device for the calibration of $^{60}$Co HDR brachytherapy sources. They can be applied to the quality assurance in clinical routine, the same as for $^{192}$Ir HDR sources.

Within the scope of the presented study, radiation quality correction factors $k_Q$ for two types of well-type chambers were determined as the ratio of the chamber calibration coefficient for $^{60}$Co HDR sources $N_{\text{Co-60}}$ and that of $^{192}$Ir HDR sources $N_{\text{Ir-192}}$. In this way, a well-type chamber calibrated for radiation fields of $^{192}$Ir sources can be used for the measurement of the reference air kerma rate of $^{60}$Co HDR brachytherapy sources without any additional calibration of the chamber. The calibration coefficient $N_{\text{Co-60}}$ for $^{60}$Co can be calculated from a given calibration coefficient $N_{\text{Ir-192}}$ for $^{192}$Ir radiation by

$$N_{\text{Co-60}} = k_Q \cdot N_{\text{Ir-192}}.
$$

The uncertainty of $k_Q$ is dominated by the contributions due to the uncertainties of the RAKR of the calibration sources and amounts to $U(k_Q) = 2.1\%$ ($k = 2$). The uncertainty of a $^{60}$Co calibration coefficient calculated via Eq. (5) from an $^{192}$Ir calibration coefficient is given by $U_{N_{\text{Co-60}}} = \sqrt{(U_{k_Q})^2 + (U_{N_{\text{Ir-192}}})^2}$. For a well-type chamber with a calibration coefficient with an uncertainty of, e.g., $U_{N_{\text{Ir-192}}} = 1.6\%$ ($k = 2$) this results in an uncertainty of $U_{N_{\text{Co-60}}} = 2.6\%$ ($k = 2$). This is twice as large as that obtained by direct calibration with a $^{60}$Co source.

If small uncertainties are important or if the $^{192}$Ir calibration coefficient of the chamber shows abnormal deviations from the typical value, a direct calibration with a $^{60}$Co source is advisable instead of the application of a radiation quality correction factor.

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Table V. Expanded uncertainty ($k = 2$) of $k_Q$ and its components.

| Component          | Uncertainty (%) | Type |
|--------------------|-----------------|------|
| RAKR of $^{60}$Co source | 1.32           | B    |
| RAKR of $^{192}$Ir source | 1.54           | B    |
| Chamber variation  | 0.4             | A    |
| $^{192}$Ir source variation | 0.14           | A    |
| $^{60}$Co source variation | 0.2            | B    |
| $k_Q$              | 2.08            |      |

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