Characterization of new primary air kerma standards for dosimetry in Co-60, Cs-137 and Ir-192 gamma ray sources

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ABSTRACT: Introduction. To be better suited for measurements at air kerma rates which are common for the calibration of detectors for dosimetry in brachytherapy and radiation protection, two graphite-wall, air-filled cavity ionization chambers (PS-10 and PS-50 built by PTW of Freiburg, Germany) were characterized for use as primary standards at the Physikalisch-Technische Bundesanstalt (PTB) for $^{60}$Co, $^{137}$Cs and $^{192}$Ir gamma ray sources.

Methods. Applying experimental or Monte Carlo methods, corrections were determined for wall effects, stem scattering effects, point-source non-uniformity, saturation effects, and deviations from Spencer-Attix cavity theory. The geometrical cavity volume of the ionization chambers was determined by a special experimental method. Non-charge-collecting parts of the volume were calculated by finite-element simulations. In addition, mass electronic stopping powers and mass-energy absorption coefficients were reevaluated in close agreement with ICRU 90. To compare the results to an already established air kerma standard, measurements of air kerma rates were taken for gamma rays from all three sources.

Results. In contrast to the standards currently in use, the newly characterized ionization chambers show significant wall effects up to 4.17% ($^{192}$Ir). For the PS-10 ionization chamber, the geometric volume differs by 0.42% from the charge collecting volume. For the $^{192}$Ir source, Spencer-Attix corrections were applied exceeding 0.30% for both ionization chambers. Applying the derived corrections factors, air kerma rates measured with the two ionization chambers at the three sources did not differ by more than 0.13%. Comparing the results to an already established air kerma standard, deviations ranged up to 0.61%. The uncertainty budget for the determination of air kerma rates resulted in a relative combined standard uncertainty of 0.35%.

Conclusion. Both ionization chambers can be used as primary air kerma standards for $^{60}$Co, $^{137}$Cs and $^{192}$Ir gamma ray sources using the values of corresponding physical quantities and correction factors derived in this work.

KEYWORDS: Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); X-ray detectors; Gaseous detectors; Ionization and excitation processes

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1 Introduction

1.1 New primary air kerma cavity standards for brachytherapy

The Physikalisch-Technische Bundesanstalt (PTB) is the national metrology institute of Germany. It offers air kerma calibration of secondary standard dosimeters for gamma rays from $^{60}\text{Co}$, $^{137}\text{Cs}$ and $^{192}\text{Ir}$ sources. These measurements are also the basis for calibrations in terms of the operative quantities for radiation protection, namely $H^*(10)$ and $H_p(10)$. For this purpose, PTB constructed three different gamma ray irradiation facilities equipped with seven $^{137}\text{Cs}$ and eight $^{60}\text{Co}$ sources of different activities and, as required, with a high-dose-rate (HDR) $^{192}\text{Ir}$ brachytherapy source. The air kerma rates in these radiation fields lie in the range of approximately 100 nGy/h to 25 mGy/s (90 Gy/h). A typical (most commonly used) HDR $^{192}\text{Ir}$ brachytherapy source is characterized by an air kerma rate at 100 cm distance of about 10 $\mu$Gy/s. For $^{60}\text{Co}$ and $^{137}\text{Cs}$, PTB uses three air-filled, graphite-walled cavity ionization chambers as primary air kerma standards. These chambers have nominal cavity volumes of between 0.5 cm$^3$ and 6 cm$^3$. The largest one is the HRK3 ionization chamber, which has a leakage current of about 5 fA and thus can be used reliably if the ionization current is at least approximately 0.5 pA, which corresponds to a dose rate of roughly 2.5 $\mu$Gy/s. This places the HRK3 close to its limits for HDR $^{192}\text{Ir}$ brachytherapy sources and all other sources of the irradiation facilities characterized by lower air kerma rates. For these reasons, PTB began looking for larger volume cavity ionization chambers for use as primary air kerma standards and found two spherical type chambers which are commercially available (PS-10 and PS-50, PTW, Freiburg, Germany). The design of these ionization chambers is based on that of the primary standard air kerma ionization chambers used at the National Institute of Standards and Technology (NIST). The sensitive volumes of these chambers are approximately 10 cm$^3$ and 50 cm$^3$ for the PS-10 and PS-50, respectively, and therefore significantly larger than that of the HRK3.

In the process of characterizing these ionization chambers, the literature was reviewed to extract a full picture of all correction factors that must be used under consideration of the currently available scientific evidence, and to develop a full formalism for establishing a primary standard.

Several important publications on this topic can be found in the literature [1–3]. This work gives a full, comprehensive description of the characterization of ionization chambers for use as primary air kerma standards for incident photon beams from $^{60}\text{Co}$, $^{137}\text{Cs}$ and $^{192}\text{Ir}$ sources. All currently known corrections are introduced and calculated, and all of the physical quantities were set in accordance with ICRU 90 [4].

1.2 Formalism for the determination of air kerma

In accordance with ICRU 90 [4], PTB derives the air kerma ($K_{\text{air}}$) from measurements by applying the Bragg-Gray theory:

$$K_{\text{air}} = \frac{T_{\text{air}}\Delta t}{V\rho_{\text{air}}} \frac{W_{\text{air}}/e}{1 - \bar{g}_{\text{air}}} \bar{s}_{e,\text{air}}(\bar{\mu}_{\text{en}}/\rho)_{\text{air},e} k_s k_{\text{an}} k_m k_{\text{st}} k_{\text{wall},ps} k_h$$  \hspace{1cm} (1.1)

Here, $T_{\text{air}}$ is the mean electric current measured between the anode and cathode of the ionization chamber over a time interval $\Delta t$. The sensitive volume $V$ is filled with air of density $\rho$. $W_{\text{air}}/e$ is the mean energy expended in dry air per ion pair formed divided by the elementary charge $e$. $\bar{g}_{\text{air}}$ is the
mean fraction of the kinetic energy of the liberated electrons that is lost by radiative processes (e.g., fluorescence radiation and bremsstrahlung). \( \bar{\eta}_{\mu_n/\rho} \) is the ratio of the mean photon-fluence weighted mass-energy absorption coefficients of air and graphite, each weighted by the photon fluence inside the graphite wall of the ionization chamber. The factor \( \bar{\eta}_{c,\text{air}} \) describes the ratio of the mass electronic stopping power of graphite and air, each weighted by the electron fluence inside the cavity of the ionization chamber. The correction factors \( k_i \) correct the first part of the equation for several effects that occur in the actual measurement situation using a real ionization chamber. As not all charges generated inside of the sensitive volume of the ionization chamber are collected by the electrode, \( \bar{\eta}_{c,\text{air}} \Delta \tau \) must be corrected by a correction factor \( k_s \) for recombination losses. Moreover, the first part of the equation holds only for a wide parallel photon beam, so a correction has to be applied for both the axial and the radial beam non-uniformity \( (k_{\text{an}}k_{\text{rn}}) \). In addition, scattered photons or electrons coming from the stem of the ionization chamber can influence the measurement. This is corrected by the correction factor \( k_{\text{st}} \). To compensate for attenuation and scattering effects in the wall of the ionization chamber, a correction factor \( k_{\text{wall,ps}} \) is applied. The humidity correction factor \( k_h \) corrects the ionization current measured in ambient humid air to that which would be measured in dry air. All of these correction factors were described in the literature and were reviewed by Büermann and Burns [3].

In this work, all quantities and correction factors (except \( k_{\text{rn}} \), as it depends on the radiation source) in equation (1.1) were determined by Monte Carlo or experimental methods. In addition to the correction factors currently used, PTB plans to introduce corrections for dead volume effects as well as a correction for deviations from conditions justifying the application of the Spencer-Attix theory as it is described in literature [5]. Further, air kerma measurements were made to compare the established HRK3 ionization chamber with the PS-10 and PS-50 ionization chambers. This work is the basis for the establishment of two new primary air kerma cavity standards for \( ^{60}\text{Co}, ^{137}\text{Cs} \) and \( ^{192}\text{Ir} \) gamma ray sources at PTB.

2 Methods

2.1 Determination of the graphite density and the collecting volume

The density of the graphite used for the construction of the PS-10 and PS-50 ionization chambers was determined by measurement. For this, the manufacturer provided cylindrical samples of the same graphite that was used in the construction of the ionization chamber.

The geometric sensitive volume of the PS-10 and PS-50 ionization chambers was determined for each by removing the ionization chambers from the stem and filling the sensitive volume with water. After this, dummy electrodes (provided by the manufacturer) were put into the ionization chamber cavities, which were adjusted to align with the dimensions of the actual electrodes. Then the water-filled ionization chambers were weighed \( (W_2) \). These measurements were repeated after removing the water from the sensitive volumes \( (W_1) \). The geometric volume of the ionization chamber was then determined by:

\[
V = (W_2 - W_1) \left( \frac{1}{\rho_w - \rho_w} \right) \left( 1 - \frac{\rho_a}{\rho_{cw}} \right)
\]  

(2.1)
Here, \( \rho_w \), \( \rho_a \) and \( \rho_{cw} \) are the densities of the water, air and calibrated weight used during the measurement.

As both the PS-10 and PS-50 ionization chambers are guarded ionization chambers, the dead volume near the guard ring must be included in the models for the Monte Carlo simulations and in the calculation of the volume of the ionization chambers. In accordance with our previous work \[6\], COMSOL Multiphysics (version 5.6) was used to calculate the geometry of the dead volumes of the ionization chambers (figure 1).

Due to its design, the unguarded HRK3 ionization chamber is not influenced by the described dead volume effects.

### 2.2 Reevaluation of the mass electronic stopping power including the Sternheimer density effect

For the calculation of the mass electronic stopping power, the equations given in ICRU 90 \[4\] were reevaluated using a Python code. This included the equations for the mass electronic stopping power and the restricted mass electronic stopping power including the Sternheimer density effect \[7, 8\]. In the calculations, the Sternheimer formulas for the density effect were solved using Powell’s method. The parameters that were used for the definition of graphite in the context of the calculation of the Sternheimer density effect are shown in table 1. The input parameters differ from the parameters that were used for the ESTAR database \[9\], where the fraction of conduction electrons was not adapted to the latest ICRU 90 recommendations \[4\].

**Table 1.** Parameters used to calculate the Sternheimer density effect for graphite. The binding energies were taken from \[10\].

| Parameter                           | Value          |
|-------------------------------------|----------------|
| Number of oscillators               | 3              |
| Atomic number                       | 6              |
| Fraction of conducting electrons    | 1/6            |
| Oscillator strengths                | 2/6, 2/6, 1/6  |
| Mean excitation energy [eV]         | 81             |
| Relative atomic mass [g/cm\(^3\)]  | 12.011         |
| Density (for density effect only) [g/cm\(^3\)] | 2.265         |
| Energy levels [eV]                  | 288, 16.59, 11.26 |

### 2.3 Air density, humidity and \( W_{air} \)

The density \( \rho_{air} \) was set to the corresponding value for dry air at 1013.25 hPa and 293.15 K: \( \rho_{air} = 1.2048\frac{kg}{m^3} \). In accordance with our previous work, the correction for humidity was set to \( k_h = 0.9970 \) \[3\]. \( W_{air} \) was set to 33.97 eV as recommended by ICRU 90 \[4\].

### 2.4 Correction factors determined by Monte Carlo simulations

#### 2.4.1 Parameters for Monte Carlo simulations

All simulations were performed using the Monte Carlo code package EGSnrc \[11\] (release version 2020).
For all Monte Carlo simulations, the energetic cutoffs were set to ECUT = 0.521 MeV (kinetic energy of 10 keV) and PCUT = 0.001 MeV for electrons and photons, respectively. The modelling of atomic relaxations was included for all simulations.

The XCOM cross-section database with renormalized Scofield photoelectric effect cross sections (mcdf-xcom) was used for photon interactions. Stopping powers were calculated in pegless mode based on density correction files. For graphite, a density correction file was created using the values obtained from the reevaluation of the Sternheimer density correction equation described above. These values were checked to align with the values tabulated in ICRU 90 [4]. The cross sections for copper, aluminium, and dry air were calculated based on the density files provided in EGSnrc. The NRC bremsstrahlung corrections were used for all simulations. All of the remaining simulation parameters were left to the default values of EGSnrc [11].

The spectra used for the modelling of the $^{60}$Co, $^{137}$Cs and $^{192}$Ir (microSelectron) sources were those included in EGSnrc [11] (release version 2020).

All simulations were performed in vacuum. In cases where an ionization chamber was modelled, the distance between the source and the reference point of the ionization chamber was set to 100 cm.

Table 2 gives an overview of all EGSnrc user codes that were used in this work.

| User code | Quantity |
|-----------|----------|
| g         | $(\bar{\mu}_{\text{en}}/\rho)_{\text{air,c}}, \bar{\sigma}_{\text{air}}, K_{\text{air,norm}}, \bar{g}_{\text{wall}}$ |
| cavity    | $k_{\text{wall,ps}}, k_{\text{wall,par}}, k_{\text{st}}$ (PS-10 and PS-50), $k_{\text{pn}}, \phi_{\text{air}}$ |

2.4.2 Ratio of mass-energy absorption coefficients and $\bar{g}_{\text{air}}$

The ratio of the mean photon-fluence weighted mass-energy absorption coefficients of air to graphite, $(\bar{\mu}_{\text{en}}/\rho)_{\text{air,c}}$, was calculated utilizing the EGSnrc user code $g$ for each beam quality. The same user code was used for the calculation of $\bar{g}_{\text{air}}$ and $\bar{g}_{\text{wall}}$.

2.4.3 Wall effects

The correction factor for wall effects ($k_{\text{wall,ps}}$) was calculated using the EGSnrc user code $cavity$, which included a method for the direct calculation of $A_{\text{wall}}$, the inverse of the correction factor for wall effects. Variance reduction was activated in the form of photon splitting, which was initialized with a photon splitting factor of 100. For the PS-10 and PS-50 ionization chambers, detailed Monte Carlo models were created based on technical drawings provided by the manufacturer (figure 1). For this part of the simulations, the stem of the ionization chambers was removed from the simulation geometry. Besides this, the geometry of the dead volume near the guard ring was excluded for dose scoring. A similar model was created for the HRK3 ionization chamber. The geometrical dimensions of the HRK3 ionization chamber can be found in the literature [12, 13].

2.4.4 Stem scattering and point-source non-uniformity

According to the literature, the correction factor for axial beam non-uniformity $k_{\text{an}}$ can be replaced by a point-source non-uniformity correction factor $k_{\text{pn}}$ [14].
For the PS-10 and PS-50 ionization chambers, the corrections for stem scattering ($k_{st}$) and point-source non-uniformity ($k_{pn}$) were calculated using the EGSnrc user code cavity. For variance reduction, photon splitting was activated with a photon splitting factor of 100. For some parts of these simulations, the models of the ionization chambers also included a detailed representation of the stem of the ionization chambers (figure 1).

For the determination of the stem effect, a photon-emitting point source was defined at 100 cm distance to the reference point of the ionization chamber. The EGS_CollimatedSource class was used here with the collimation set to a circle with a radius of 15 cm at 100 cm distance (at the reference point of the ionization chamber). The deposited energy was scored in the sensitive volume of the ionization chamber and normalized to the primary photon fluence by the user code ($E_{ps,stem}$). The simulation was repeated for ionization chamber models that did not include the stem of the ionization chambers, resulting in the quantity $E_{ps,w/o\ stem}$. The ratio of these results was used for the calculation of the $k_{st}$:

$$k_{st} = \frac{E_{ps,w/o\ stem}}{E_{ps,stem}}$$  \hspace{1cm} (2.2)

For the correction of stem scattering effects of the HRK3 ionization chamber, previously published values were taken from the literature [12, 13]. As no experimental results have been published for $^{192}$Ir and no significant difference was observed when comparing the results for $^{60}$Co to the results for $^{137}$Cs, the stem scattering correction determined for $^{137}$Cs was also used for the $^{192}$Ir radiation quality in connection with the HRK3 ionization chamber.

In another simulation (using the same user code and simulation parameters), the point source was replaced by a parallel beam emerging from a circle with a radius of 15 cm. Again, the energy was scored in the sensitive volume of the Monte Carlo models of all ionization chambers (excluding the stem) and normalized to the primary photon fluence ($E_{par,w/o\ stem}$). In addition, a correction factor for wall effects in a broad parallel beam ($k_{wall,par}$) was calculated. Then the correction factor for the point-source non-uniformity was calculated as described in [3]:

$$k_{pn} = \frac{E_{par,w/o\ stem}}{E_{ps,w/o\ stem}} \frac{k_{wall,par}}{k_{wall,ps}}$$  \hspace{1cm} (2.3)

Figure 1. Monte Carlo models of the PS-10 and PS-50 ionization chamber. The red volume marks the dead volume calculated by FEM simulations that was excluded for dose scoring.
2.4.5 Stopping power ratios

For all ionization chambers, the values resulting from the reevaluation of the equations for the mass electronic stopping power were used to calculate the stopping power ratio ($s_{c/air}$) by applying the Spence-Attix equation given in ICRU 90 [4]:

$$s_{c/air} = \frac{\int_{T_{max}}^{T_{\Delta}} \phi_{T}^c (S_{\Delta}/\rho) dT + \phi_{T}^c (S/\rho)_{c} \Delta}{\int_{T_{max}}^{T_{\Delta}} \phi_{T}^c (S_{\Delta}/\rho)_{air} dT + \phi_{T}^c (S/\rho)_{air} \Delta}$$

(2.4)

Here, $S_{\Delta}/\rho$ is the restricted mass electronic stopping power and $S/\rho$ the unrestricted mass electronic stopping power of the corresponding material for electrons.

According to ICRU 90, the recommended choice for the cutoff energy $\Delta$ depends on the mean free cord length of the ionization chamber under investigation [4]. As the pancake ionization chamber of the BIPM (International Bureau of Weights and Measures, Paris, France) and the NIST 10 cm$^3$ and 50 cm$^3$ ionization chambers are, respectively, very similar to the HRK3, PS-10 and PS-50 ionization chambers, $\Delta$ was chosen in accordance with the values published by Borg et al. [15] (10.29 and 42 keV). The maximum kinetic energy $T_{max}$ was set to 1.15 MeV.

The electron fluence inside the sensitive volume of the ionization chambers ($\phi_{T}^c$) was calculated using the EGSnrc user code cavity. For this purpose, the fluence was scored logarithmically in 100 bins in the range of 0.01–1.5 MeV. In agreement with the simulations described above, the photon splitting factor was set to 100. The source was modelled as a parallel beam with a radius of 15 cm at 100 cm distance to the reference point of the ionization chamber. Here, the stem of the ionization chamber was not included in the simulations and the dead volume was removed from dose scoring. The integration was performed numerically by Simpson’s rule.

2.4.6 Spencer-Attix correction factors

For lower photon energies, the number of photons interacting with the air in the sensitive volume of an ionization chamber increases, which invalidates Bragg-Gray conditions. To account for these effects, a Spencer-Attix correction factor can be calculated as was previously described in the literature [15]:

$$k_{sa} = \frac{K_{air,norm}(1 - \bar{g}_{wall})}{D_{par,w/o stem} k_{par,wall} s_{c,air}(\bar{\mu}_{en}/\rho)_{air,c}}$$

(2.5)

In this equation, $D_{par,w/o stem}$ is the deposited dose to air in the sensitive volume of the ionization chamber that does not suffer from any stem scattering effects, irradiated by a broad, parallel beam. $K_{air,norm}$ is the air kerma at the point of measurement in the absence of the ionization chamber.

$K_{air,norm}$, $\bar{g}_{wall}$ and $(\bar{\mu}_{en}/\rho)_{air,c}$ were calculated using the EGSnrc user code g. For all ionization chambers, $D_{par,w/o stem}$ and $k_{wall,par}$ resulted from a Monte Carlo simulation with the user code cavity that applied the same simulation parameters as for the determination of the correction for wall effects. In this simulation, the models of the ionization chamber included the dead volume but did not include the stem of the ionization chambers.
2.5 Ionization chamber measurements

2.5.1 Saturation effects and measurement of air kerma rates

Measurements for the determination of saturation effects were performed for the PS-10 and PS-50 ionization chambers at PTB’s gamma ray irradiation facilities. This involved placing each ionization chamber at a distance of 100 cm in front of a $^{137}$Cs source and measuring the collected charge per time using a Keithley 616 Electrometer (Keithley Instruments of Solon, Ohio, U.S.A.). At the time of measurement, the air kerma rate at the point of measurement was approximately $10.3 \mu$Gy/s. Measurements were taken in the range of 50–500 V for the PS-10 ionization chamber and in the 200–500 V range for the PS-50 chamber. The data points were acquired in steps of 50 V for both polarities. These results have been used to calculate the correction for initial recombination effects. To this end, the collected charge was corrected for polarity, air temperature and pressure effects and then normalized to the resulting value for the working voltage (500 V). Subsequently, a linear regression was performed on the inverse of the normalized charge per time against the inverse of the applied voltage (Jaffé plot [16]) to calculate the correction factor for saturation effects ($k_s$).

For the HRK3 ionization chamber, $k_s$ was taken from the literature [12, 13]. In addition, measurements were taken for all ionization chambers (PS-10, PS-50 and HRK3) at 100 cm distance to a $^{60}$Co source and at 100 cm distance to a $^{137}$Cs source. These measurements were used to calculate the air kerma rate $K_{\text{air}}/\Delta t$ in accordance with equation (1.1). To compare these results between the different chamber types, the mean air kerma rate $K_{\text{air}}/\Delta t$, which is the average kerma rate over all ionization chambers, was also calculated in order to compare the value $K_{\text{air}}/\Delta t = K_{\text{air}}/\Delta t$ for the ionization chambers under investigation.

$^{192}$Ir. The measurements for the $^{192}$Ir beam quality were also carried out at PTB’s gamma ray irradiation facilities. Here, the source (microSelectron Version 2) was positioned in the centre of a 30 cm $\times$ 30 cm $\times$ 40 cm lead box equipped with a 5.5 cm diaphragm. Then a commercial industrial robot (with a positioning uncertainty of less than 0.1 mm) was used to position the ionization chambers (PS-10, PS-50 and HRK3) for measurements of the collected charge per time at different distances in the range of 80 cm to 160 cm. A linear regression was then applied to determine the ratio of the squared measurement current and the source detector distance. The idea behind this procedure was to eliminate uncertainties which occur due to the positioning of the source by the afterloading system. The collected charge per time was measured using a Keithley 6517 Electrometer (Keithley Instruments of Solon, Ohio, U.S.A.).

Finally, these results were used to calculate the $K_{\text{air}}/\overline{K}_{\text{air}}$ at a distance of 100 cm.

3 Results

3.1 Determination of the graphite density and the collecting volume

Figure 2 shows the outer contour of the dead volumes calculated with COMSOL Multiphysics for the PS-10 and PS-50 ionization chambers. Based on this, the dead volume was calculated as the solid of revolution. This resulted in 0.0420 cm$^3$ and 0.0456 cm$^3$ for the PS-10 and PS-50 ionization chamber, respectively. This correlates to a reduction in the sensitive volume of 0.42% for the PS-10 ionization chamber and of 0.09% for the PS-50. The resulting corrected volume ($V_{\text{corr}}$) is given in
Table 3, which also includes the results of the determination of the density of the wall material of all ionization chambers ($\rho_c$) and the geometrical volume ($V$).

![Figure 2](image)

**Figure 2.** Outer contour of the dead volume calculated by FEM for the PS-10 and PS-50 ionization chambers.

| Quantity       | PS-10        | PS-50       | HRK-3       |
|----------------|--------------|-------------|-------------|
| $V \,[\text{cm}^3]$ | 10.045(13)   | 49.948(64)  | 6.1380(79)  |
| $\rho_c \,[\text{g/cm}^3]$ | 1.839        | 1.821       | 1.775       |
| $V_{\text{corr}} \,[\text{cm}^3]$ | 10.003(13)   | 49.902(64)  | -           |

Table 3. Density of the wall material (graphite) and volume of all ionization chambers. $V_{\text{corr}}$ represents the volume of the sensitive volume of the ionization chambers after correcting for dead volume effects.

### 3.2 Reevaluation of the mass electronic stopping power including the Sternheimer density effect

Figure 3 shows the restricted as well as the unrestricted mass electronic stopping powers that were calculated by reevaluation of the equations given in ICRU 90 [4]. In addition, figure 3 shows the normalized cavity electron fluence calculated for the PS-10 ionization chamber. The fluence is presented for one ionization chamber only since no significant differences were found when comparing the different chamber geometries. For higher energies, the restricted electronic stopping power resulted in lower values than the unrestricted electronic stopping power, but both curves converged with decreasing energy. The collisional electronic stopping powers of the wall material (graphite) were close to the collisional electronic stopping powers of air for all energies under investigation.

### 3.3 Correction factors for all ionization chambers

The resulting correction factors are shown in table 4 to table 6 and will be described in more detail in the following. The value of $W_{\text{air}}/e$ was set to 33.97 eV for all calculations.
Figure 3. Normalized electron fluence inside the PS-10 ionization chamber and the mass stopping power used for the calculation of the stopping power ratios. For $^{192}$Ir some bumps are notable in the electron fluence, which can be explained by clusters of spectral lines in the $^{192}$Ir spectrum around 300, 500 and 600 keV.

3.3.1 Ratio of mass-energy absorption coefficients and $\bar{\gamma}$

For all radiation qualities, there were only minor differences in $(\overline{\mu}_{\text{en}}/\rho)_{\text{air,c}}$ when comparing the results for the different densities of the wall material in the ionization chambers. Moreover, the results for the $^{60}$Co beam quality were very close to those for the $^{137}$Cs beam quality, with differences of less than 0.2%. Comparing these results to the results for $^{192}$Ir, $(\overline{\mu}_{\text{en}}/\rho)_{\text{air,c}}$ increased by approximately 0.5%. For the radiation qualities $^{60}$Co and $^{137}$Cs, $(\overline{\mu}_{\text{en}}/\rho)_{\text{wall}}$ exceeded $(\overline{\mu}_{\text{en}}/\rho)_{\text{air}}$, while the opposite was observed for $^{192}$Ir.

Radiative losses of the electrons in the wall material were most pronounced for $^{60}$Co, where about 0.3% of the energy was lost. For the lower energies of $^{137}$Cs and $^{192}$Ir, the portion of radiative losses decreased to about 0.1%.

3.3.2 Wall effects

For $^{60}$Co, wall effects were almost negligible for the HRK3 ionization chamber. This was not the case for the PS-10 and PS-50 ionization chambers, where the correction already exceeded 2.4% for the PS-10 and 2.7% for the PS-50. For the $^{137}$Cs and $^{192}$Ir radiation qualities, wall effects for the PS-10 and PS-50 ionization chambers respectively exceeded 3.2% and 3.6% ($^{137}$Cs) and 3.5% and 4.1% ($^{137}$Ir). For these radiation qualities, the HRK3 also required wall effect correction, which amounted to approximately 0.2% ($^{137}$Cs) and 0.8% ($^{137}$Ir).

3.3.3 Stem scattering and point-source non-uniformity

The stem scattering effect correction factors calculated by Monte Carlo methods show that scattering effects slightly increased the deposited dose in the sensitive volume of all ionization chambers. The PS-10 ionization chamber was influenced most by stem scattering effects, while the influence on
the PS-50 chamber was comparable to the results for the HRK3 ionization chamber. There seems to be a slight increase of scattering effects for lower energy radiation qualities. For example, while stem scattering effects increased the dose in the sensitive volume of the PS-10 ionization chamber by about 0.2% for $^{60}$Co, there was an increase of approximately 0.4% for the $^{192}$Ir beam quality.

This contrasts to the effect of the point-source non-uniformity, which did not depend on the radiation quality. The spherical ionization chambers, PS-10 and PS-50, were not significantly influenced by this effect, while the response of the HRK3 parallel-plate ionization chamber was a change of more than 0.2% for all radiation qualities.

### 3.3.4 Stopping power ratios

The investigations showed a clear dependence on the radiation quality. While $(S/\rho)_{\text{wall}}$ exceeded $(S/\rho)_{\text{air}}$ for $^{60}$Co by approximately 0.5%, $(S/\rho)_{\text{air}}$ exceeded $(S/\rho)_{\text{wall}}$ by more than 0.3% for $^{137}$Cs and by more than 0.6% for $^{192}$Ir. For each beam quality, a difference of no more than 0.1% was found between the different ionization chambers.

### 3.3.5 Spencer-Attix correction factors

For $^{60}$Co, the simulation results showed a deviation of less than 0.04% from Spencer-Attix theory, which is within the variance of the Monte Carlo simulations. The effect was similar for all ionization chambers under investigation. Deviations from Spencer-Attix theory increased with decreasing energy. For $^{192}$Ir, there was a deviation of more than 0.3% for all ionization chambers.

### 3.3.6 Saturation effects

The resulting Jaffé plots are shown in figure 4. For both ionization chambers (PS-10 and PS-50) a linear behaviour was observed. The linear fit was found to be within the uncertainty intervals of each individual data point, which were derived by propagation of uncertainty from the standard deviation of the measurement of the electric current between the collecting electrode and the wall of the ionization chamber. The linear regression resulted in $k_s = 1.0010$ for the PS-10 ionization chamber and $k_s = 1.0025$ for the PS-50 ionization chamber.

![Figure 4](image.png)

**Figure 4.** Linear regressions for the determination of saturation effects.
Table 4. Results for $^{60}$Co.

| Quantity       | PS-10   | PS-50   | HRK3    |
|----------------|---------|---------|---------|
| $\rho$ [kg/m$^3$] | 1.2048  | 1.2048  | 1.2048  |
| $(\bar{p}_{\text{en}}/\rho)_{\text{air,c}}$ | 0.9988  | 0.9988  | 0.9977  |
| $\bar{\sigma}_\text{air}$ | 0.0032  | 0.0032  | 0.0032  |
| $k_{\text{wall,ps}}$ | 1.0241  | 1.0271  | 1.0002  |
| $k_{\text{st}}$ | 0.9982  | 0.9991  | 0.9992  |
| $k_{\text{pn}}$ | 1.0000  | 0.9999  | 1.0024  |
| $\bar{\sigma}_{c,\text{air}}$ | 0.9945  | 0.9942  | 0.9949  |
| $k_{\text{sa}}$ | 0.9997  | 0.9998  | 0.9996  |
| $k_s$ | 1.0010  | 1.0025  | 1.0011  |

Table 5. Results for $^{137}$Cs.

| Quantity       | PS-10   | PS-50   | HRK3    |
|----------------|---------|---------|---------|
| $\rho$ [kg/m$^3$] | 1.2048  | 1.2048  | 1.2048  |
| $(\bar{p}_{\text{en}}/\rho)_{\text{air,c}}$ | 0.9989  | 0.9989  | 0.9977  |
| $\bar{\sigma}_\text{air}$ | 0.0012  | 0.0012  | 0.0012  |
| $k_{\text{wall,ps}}$ | 1.0322  | 1.0360  | 0.9979  |
| $k_{\text{st}}$ | 0.9974  | 0.9989  | 0.9989  |
| $k_{\text{pn}}$ | 1.0001  | 0.9999  | 1.0022  |
| $\bar{\sigma}_{c,\text{air}}$ | 1.0033  | 1.0029  | 1.0038  |
| $k_{\text{sa}}$ | 0.9984  | 0.9990  | 0.9987  |
| $k_s$ | 1.0010  | 1.0025  | 1.0011  |

Table 6. Results for $^{192}$Ir.

| Quantity       | PS-10   | PS-50   | HRK3    |
|----------------|---------|---------|---------|
| $\rho$ [kg/m$^3$] | 1.2048  | 1.2048  | 1.2048  |
| $(\bar{p}_{\text{en}}/\rho)_{\text{air,c}}$ | 1.0026  | 1.0026  | 1.0023  |
| $\bar{\sigma}_\text{air}$ | 1.0010  | 1.0010  | 1.0010  |
| $k_{\text{wall,ps}}$ | 1.0352  | 1.0417  | 0.9925  |
| $k_{\text{st}}$ | 0.9962  | 0.9982  | 0.9989  |
| $k_{\text{pn}}$ | 1.0001  | 1.0001  | 1.0023  |
| $\bar{\sigma}_{c,\text{air}}$ | 1.0065  | 1.0061  | 1.0071  |
| $k_{\text{sa}}$ | 0.9969  | 0.9967  | 0.9963  |
| $k_s$ | 1.0010  | 1.0025  | 1.0011  |
3.4 Determination of air kerma rates

Table 7 and figure 5 show the results when applying all the previously described correction factors to measurements for all beam qualities. For the PS-10 and PS-50, the derived air kerma rates never deviated by more than 0.13%. Comparing these results to the results derived from the HRK3 measurements, it was found that applying the derived correction factors to the HRK3 measurements led to an air kerma rate that exceeded the PS-10 and PS-50 value by about 0.5% for all radiation qualities.

Table 7. Air kerma rates determined by applying the described correction factors for all radiation sources used during the experiments. All values have been corrected to the same reference date.

| Source | PS-10      | PS-50      | HRK-3      |
|--------|------------|------------|------------|
| $^{60}$Co | 1.5004(51) | 1.4985(53) | 1.5047(54) |
| $^{137}$Cs | 12.094(41) | 12.101(43) | 12.149(43) |
| $^{192}$Ir | 13.368(47) | 13.376(47) | 13.450(48) |

![Figure 5](image_url). Comparison of $K_{air}/\bar{K}_{air}$ for all ionization chambers and radiation qualities under investigation.

3.4.1 Uncertainty budget

The uncertainties of $\rho$, $(\bar{\rho}_{en}/\rho)_{air,c}$, $\bar{\rho}_{air}$, $k_{th}$, $k_s$ and $I$ were chosen in accordance with our previous work [3, 12, 13]. The uncertainty of the product $W_{air}t_{c,a}/e$ was chosen in accordance with the work of Burns et al. [17]. The type A uncertainties of $k_{wall,ps}$, $k_{st}$, $k_{pn}$ and $k_{sa}$ represent the statistical uncertainties of the Monte Carlo simulations. For $k_{wall}$, an additional type B uncertainty was added to account for possible differences between the wall thickness of the Monte Carlo model and the thickness of the wall of the actual ionization chamber. As the calculation of $k_{pn}$ and $k_{sa}$ would also be affected by such deviations, the same type B uncertainty was assumed for these correction factors. Also, an additional type B uncertainty was included for $k_{st}$ to account for possible differences between the Monte Carlo and the actual geometry of the ionization chambers. In general, the uncertainties of $K_{air}/\bar{K}_{air}$ were calculated by propagation of uncertainties, but the uncertainties of $\rho$, $(\bar{\rho}_{en}/\rho)_{air,c}$ and $\bar{\rho}_{air}$ were not included in this calculation as the same values were used for all ionization chambers.
Table 8. Uncertainty budget for the PS-10 and PS-50 ionization chambers. As the uncertainty for the product $W_{\text{air} \beta_{c,a}/e}$ differs slightly for the different beam qualities, one uncertainty is given for $^{60}\text{Co}$ and another for $^{137}\text{Cs}$ and $^{192}\text{Ir}$. Here, $s_i$ represents the relative standard uncertainty estimated by statistical methods (type A) and $u_i$ represents the relative standard uncertainty estimated by other means (type B).

| Quantity               | $s_i$ [%] | $u_i$ [%] |
|------------------------|-----------|-----------|
| $\rho$                 | 0.01      |           |
| $(\bar{\mu}_{cn}/\rho)_{\text{air,c}}$ | 0.05      |           |
| $W_{\text{air} \beta_{c,a}/e}$ | 0.08/0.12 |           |
| $\bar{\sigma}_{\text{air}}$ | 0.02      |           |
| $k_{\text{wall,ps}}$   | 0.02      | 0.15      |
| $k_{\text{st}}$        | 0.02      | 0.05      |
| $k_{\text{pn}}$        | 0.02      | 0.15      |
| $k_{\text{s}}$         | 0.05      | 0.05      |
| $k_{h}$                | 0.03      |           |
| $k_{\text{an}}$        | 0.20      |           |
| $k_{\text{sa}}$        | 0.02      | 0.15      |
| $V$                    | 0.08      | 0.1       |
| $I$                    | 0.01      | 0.02      |
| **Combined uncertainty in %** | **0.35/0.36** |           |

4 Discussion

In this work, the foundations were laid for two new primary standards for $^{60}\text{Co}$, $^{137}\text{Cs}$ and $^{192}\text{Ir}$ gamma ray sources at PTB. All of the necessary quantities in equation (1.1) were determined by state-of-the-art methods and in close agreement with the recommendations of ICRU 90 [4]. In contrast to previous work, investigation was also made of the influence of dead volumes inside guarded ionization chambers and of a correction factor for deviations from Spencer-Attix theory.

The correction for the deviation from Spencer-Attix theory ($k_{\text{sa}}$) can be compared to the results of Borg et al. [15], who calculated $k_{\text{sa}}$ for both the BIPM pancake ionization chamber and the NIST 10 cm$^3$ and 50 cm$^3$ ionization chambers, which are similar to the HRK-3, PS-10 and PS-50 ionization chambers, respectively. While the results of the present work confirm the results of Borg et al. with respect to the BIPM pancake ionization chambers for $^{60}\text{Co}$ and $^{192}\text{Ir}$, there are significant differences when it comes to the spherical ionization chambers under investigation. The reason for this deviation is unclear. The results of Borg et al. show that the geometry can have an impact on the $k_{\text{sa}}$ correction factor, with the authors suggesting a correction of about 0.3% for the BIPM pancake ionization chamber and the $^{192}\text{Ir}$ beam quality while stating that no corrections are necessary for the NIST 10 cm$^3$ and 50 cm$^3$ ionization chambers for the $^{192}\text{Ir}$ beam quality. As such, the deviations described in the present work could be explained by minor geometrical differences between the NIST and PTW ionization chambers (e.g., the different size of the electrode).

As concerns the air kerma rate measurements shown above, the results from the PS-10 and PS-50 ionization chambers align within less than 0.15% for all beam qualities. There seems to be a systematic offset to the HRK3 ionization chamber, whose air kerma rate measurement results
exceed those of the PS-10 and PS-50 ionization chambers by approximately 0.5% for all beam qualities. As the calculation of most of the correction factors were based on the same principles for all ionization chambers, this difference might be linked to the determination of the sensitive volume of the ionization chambers. In a recent key comparison [12, 13], the HRK3 ionization chamber was also compared to the BIPM primary standard for $^{60}\text{Co}$ and $^{137}\text{Cs}$. In this comparison, the air kerma rates measured with the HRK3 ionization chamber exceeded the values derived from the BIPM primary standard by 0.40(17)% and 0.24(27)% for $^{60}\text{Co}$ and $^{137}\text{Cs}$, respectively. From these results, it can be concluded that the results obtained from the PS-10 and PS-50 measurements are in close agreement with the BIPM primary standard.

With all factors taken into consideration, all of the resulting air kerma rates align with the estimated relative uncertainty of 0.35% ($k = 1$), meaning that the derived values for the calculation of air kerma can be used for the establishment of a primary standard for all purposes where this uncertainty sufficiently covers the given needs.

5 Conclusion

When the corrections presented here are applied, the deviations between the air kerma rates derived from measurements lie within 0.61% for the three different cavity ionization chambers (PS-10, PS-50, HRK3) at the three different beam qualities. For the PS-10 ionization chamber, the geometrical volume cannot be set equal to the actual sensitive volume as it deviates by more than 0.4%. For the $^{192}\text{Ir}$ beam quality, it is necessary to introduce Spencer-Attix correction factors for all ionization chambers under investigation. All preparations have now been completed for the establishment of new primary air kerma standards for $^{60}\text{Co}$, $^{137}\text{Cs}$ and $^{192}\text{Ir}$ gamma ray sources.

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