ABSTRACT

Before clinical use of a brachytherapy source, regulations or recommendations by medical physics societies require an independent measurement of its air kerma strength by a qualified medical physicist. Currently, in addition to Ir-192, also HDR-Co-60 sources are increasingly coming into operation. However, the existing dosimetry protocols do not provide any guidelines for Co-60 sources. The purpose of this work was therefore to compare air kerma rate measurements as recommended by different dosimetry protocols for Ir-192 HDR sources and to test their applicability to Co-60 sources. Dosimetric verification of HDR afterloading source specification was performed according to three protocols, DIN 6809-2 (1993) in combination with DGMP-Report 13 (2006), IAEA-TECDOC-1274 (2002) and AAPM Report 41 (1993) for the nuclides Ir-192 and Co-60. Measurements of the sources reference air kerma rate were performed with 3 different methods (with a cylindrical chamber both in a solid phantom and in free air, and with a well chamber) and evaluated using all three protocols for each type of source and method of measurement. The measurements with all protocols and methods show deviations from the certified specification smaller than about 1.2% for Ir-192 and 2.5% for Co-60 Sources. The measurements with the well chamber showed the lowest deviations from the certificate value. Air kerma rate measurements for Co-60 HDR sources using the existing protocols are possible with accuracy sufficient to verify source calibration as provided by the source certificate. However, extension of the protocols by correction factors for measurement with Co-60 sources would be helpful.

Key words: Air kerma rate measurement for Ir-192, Co-60, brachytherapy, dosimetry

Introduction

In modern brachytherapy, dose calculations are usually performed with a standardised formalism developed and published by Task Group 43 (TG 43) of the Radiation Therapy committee of the American Association of Physicists in Medicine (AAPM). This formalism uses sets of standardised calculation factors which are determined makes use of dosimetry data obtained by measurement and/or Monte-Carlo calculation for each type and design of source. The adaption of the calculation to the individual source (and its activity) is achieved by its air kerma strength which is defined as $S_k = K_k(d) \cdot d^2$ the air kerma rate $K_k(d)$ at distance $d$ in vacuo due to photons of energy greater than $\delta$, multiplied by $d^2$. In the TG 43 report, for convenience, the unit of air kerma strength is called U where $1 \text{U} = 1 \text{cGy h}^{-1} \text{cm}^2 = 1 \mu\text{Gy h}^{-1}$. In most other modern protocols and recommendations for brachytherapy dosimetry (IAEA TECDOC 1274, DIN 6809-2, ESTRO Physics booklet No.8, ICRU 58, ICRU 58, ...) the quantity used for this adaption is the reference air kerma rate in air $K_R$, which can be measured in free in air. Usually, identical numerical values are used for $K_R$ and $K_k$, and $K_R$ is specified at 1 m distance in units of $\mu\text{Gy h}^{-1}$. 

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For commercial brachytherapy sources, air kerma strength or reference air kerma rate is specified in the source’s calibration certificate provided by the manufacturer, typically with an accuracy of ±5%. Dosimetry recommendations and regulations in practically all countries require an independent measurement air kerma rate (called dosimetric verification in the following text) by a medical physicist before therapeutic applicatiaon of the source. In case of larger deviations between measurement and manufacturer specification, the reason for the deviation should be determined.[4,9]

The most common nuclide used in modern HDR afterloading machines presently is Ir-192, however, use of Co-60 is increasing. The dimensions of the modern sources of these two isotopes are almost identical.[10] Due to the lower specific activities achievable for Co-60 the available sources typically have a lower activity of around 74 GBq (in comparison to 370 GBq for Ir-192). Nevertheless, treatment times required for 74 GBq Co-60 is only 1.8 times longer than that of a comparable 370 GBq Ir-192 due to the higher air kerma rate constant $\Gamma_0$ (around 0.306 $\mu$Gy h$^{-1}$ m$^2$/MBq for Co-60 sources in comparison to 0.099-0.11 $\mu$Gy h$^{-1}$ m$^2$/MBq for the commercially available Ir-192 sources).[10]. Dose distributions for Co-60 and Ir-192 are nearly identical, so that Co-60 may be an attractive alternative to Ir-192. The advantage of Co-60 is its longer half-life of over five years in comparison to 74 days for Ir-192 so that Co-60 sources need to be replaced only at periods of several years. This may reduce effort and costs for Ir-192. Moreover, due to the longer half-life Co-60 is increasing. The dimensions of the modern sources especially interesting for developing countries.

Recommendations for dosimetric verification of air kerma strength for afterloading sources are given in IAEA-TECDOC 1274,[1] AAPM Report 41,[12] for Germany in DIN 6809-2,[4] in combination with DGMP Report 13[5] and in ESTRO Physics booklet No.8.[6] While DGMP Report 13 and the ESTRO physics booklet[6] (which is not used in this work) describe measurements using a thimble ionization chamber free in air and in a PMMA solid phantom and using a well-type chamber the other two reports only give recommendations for measurements free in air and with a well chamber. Dosimetric parameters to calculate air kerma rate from instrument reading for the measurement of Ir-192 are given in DGMP Report 13, in IAEA-TECDOC 1274 and in the ESTRO physics booklet, while in AAPM Rept. 41 they are missing. None of the protocols is intended for calibration of Co-60 sources and therefore none provides these parameters for Co-60.

Several publications in literature describe dosimetric verification of Ir-192 sources using DGMP Report 13 and IAEA-TECDOC 1274.[9,13,14] First measurements with Co-60 sources using the new Bebig afterloader have been reported in 2006 and 2008.[15,17]

Purpose of this work is to compare dosimetric verification of Ir-192 and Co-60 afterloading sources applying all three protocols to measurements with all three methods above. Results are discussed in comparison to each other and to recent publications. This present work is a modification of a German version of current publication.[17]

Materials and Methods

Dosimetry was performed according to all three protocols mentioned above. Ir-192 measurements were performed with the Nuclertron afterloader while Co-60 measurements were performed with the Bebig Multisource afterloading machine which can operate both Ir-192 and Co-60 sources. The measurements were performed within a time period of about one year with 4 different Ir-192 and 2 Co-60 sources at three different institutions.

Two different thimble chambers (M31013 and M23331, both PTW, Freiburg) and one well-type chamber (077.094-25208, PTW Freiburg) were used for the measurements. All chambers were calibrated at the PTW Freiburg secondary standard laboratory. Chambers were calibrated in terms of absorbed dose to water ($N_w$), in air kerma ($N_a$) and in exposure ($N_x$) following the three dosimetry protocols.[1,4,12] Thimble chamber calibration factors $N_w$ were specified for Co-60 together with a radiation quality correction factor $k_q$ for 250 kV X-rays while $N_x$ and $N_a$ were provided for Co-60, Cs-137 and 250 kV X-rays. The well-type chamber was calibrated directly in terms of reference air kerma rate or exposure rate both for Co-60 and Ir-192. Measurements were performed with a UNIDOS E electrometer (PTW Freiburg) in electrical units (nC or nA). The free-in air measurements were performed with the M23331 chamber (chamber volume 1 cm$^3$), measurements in the PMMA phantom with the M31013 chamber (0.3 cm).

Table 1 lists all methods of measurement for both isotopes together with the protocols used for evaluation: measurements free-in air and in the well-type chamber were performed and evaluated according all three protocols, in the PMMA phantom AL 9193 (PTW Freiburg, “Krieger” phantom) measurements followed DIN 6809-2 (1993).[4] Measurements in a water phantom are not reported in this work. All protocols give recommendations only for Ir-192, correction factors for Co-60 were taken from literature.[10,15,16,18]

Measurement of reference air kerma rate

This section describes the measurement of the reference air kerma rate at 1m distance in air. Some publications specify air kerma rate in vacuo.[2,10] This difference is not corrected for in this work. Integration time, i.e. the dwell time of the source in the measuring position for measurements free-in-air and in the PMMA phantom was always 3 mins. Transfer time from and back to the
after loader is not accounted for. Immediately before each series of free-in-air or well chamber measurements the dwell position providing maximal dose rate was determined, and used in the following measurements. In the free-in-air and well chamber measurements the reading introduced in the evaluation of air kerma rate was determined as the average charge collected for five measurements. The reading of the well type chamber was the electrical current after arriving at a constant value. These measurements were performed only once after verifying that the maximum dose rate does not change for repeated measurements. The readings were introduced into the following formulae to calculate reference air kerma rate. In the formulae the abbreviations for factors are explained only at their first occurrence.

Measurement of air kerma rate with a thimble ionization chamber in a solid phantom following DIN 6809-2 in combination with DGMP Rept. No. 13:

Figure 1 shows the set-up for the cylindrical PMMA phantom 9193 (diameter 20 cm, length 13 cm) together with the Bebig after loader during measurements for a Co-60 source. An insert in the centre accommodates a needle in which the source is positioned. Four additional inserts measuring probes are placed symmetrically with their centre at 8cm distance from the phantom axis. Four measurements are performed, in which the ionization chamber is alternately positioned in each insert. The remaining bores are filled with dummy inserts.

Reference air kerma rate \( K_R \) is determined following the equation\(^{(4,5)}\):

\[
K_R [\text{mGy/h}] = \frac{1}{(1-g_w)} \frac{1}{t_{w/a}^\text{en}} k_{wp} k_{zp} k_r k_T k_A k_S k_r N_w [\text{mGy/nC}] M [\text{nC}]
\]

where

- \( g_w \): is the fraction of energy of the electrons from the source decay liberated by photons in water that is lost to radiative processes (mostly bremsstrahlung)
- \( t_{w/a}^\text{en} \): is the ratio water/air of the mean mass-energy absorption coefficients (\( t_{w/a}^\text{en} = 0.900 \) for Co-60 and Ir-192)

\( k_{wp} \): is a correction factor accounting for the differences in scatter and distortion of the radiation field between water and PMMA (\( k_{wp} = 1.000 \) für Co-60 und Ir-192)

\( k_{zp} \): is a correction factor accounting for the differences in scatter and absorption in the PMMA phantom surrounding the measuring probe in comparison to free-in-air conditions. This factor is also referred to in the remaining text as the phantom calibration factor.

\( k_r = \left( \frac{r_M}{r_0} \right)^2 \): is the correction for a measuring distance \( r_M \) between probe and source in relation to the reference distance \( r_0 \) for \( r_0 = 100 \text{ cm} \)

\( k_T = 60/(T/\text{min}) \) with \( T \): measuring time in min

\( k_r \): correction for attenuation and scatter by the applicator (source holder)

\( k_p \): correction factor for polarisation effect of the ionization chamber

\( k_z \): correction factor for recombination losses in the ionization chamber

\( k_a \): air density correction for differing temperature and air pressure from reference conditions

\( k_q \): correction factor for the different response of the ionization chamber at the measured radiation quality in comparison to the calibration quality Co-60

\( N_w \): calibration factor of ionization chamber in terms absorbed dose to water

\( M \): reading in nC

Values for the factors used in this work are given in Tables 2-4.

Measurement of reference air kerma rate with a thimble ionization chamber free in air following DIN 6809-2 in combination with DGMP Rept. 13:

Source and ionization chamber are positioned on a calibration jig shown in Figure 2. On the jig the distance...
source–chamber can be varied at continuous positions between 5 and 80 cm by moving the chamber holder on a rail. A mm scale allows adjusting the distance between chamber axis and source axis within an uncertainty of 0.5 mm. A second holder on the rail allows mounting a lead block between chamber and source which is used to absorb direct radiation from the source and thus measure the scatter radiation component in the air kerma measurement. The block has the same height as the sensitive volume of the ionization chamber (plus Co-60 build-up cap) and a shielding thickness of 7 cm. The block is placed immediately next to the ionization chamber. All free-in-air measurements were performed with a Co-60 build-up cap.

Reference air kerma rate $K_R$ is then determined following the equation:

$$K_R [\text{mGy/h}] = k_{air} \frac{k_{\text{app}}}{k_{\text{pmma}}} \frac{1}{l_{\text{eff}} \cdot c_m} \frac{1}{(1 - g_s)} \frac{k_{\text{air}}}{k_{\text{scat}}} \frac{k_{\text{app}}}{k_{\text{pmma}}} N_w [\text{mGy/nC}] M [\text{nC}]$$
where:

$k_{ai}$: Correction for losses of primary radiation due to scatter and attenuation in the air between source and ionization chamber \((k_{ai}(r_{M}) = \exp[\mu r_{M}] \text{ with } \mu = 0.00011/\text{cm for Ir}-192\text{ and Co}-60)\)

$k_{w \rightarrow a}$: Is a correction factor accounting for the differences in scatter and radiation field distortion in air surrounding the measuring probe in comparison to water \((k_{w \rightarrow a} = 1.000\text{ for Ir}-192\text{ and Co}-60)\)

$g_a$: Is the fraction of energy of the electrons from the source decay liberated by photons in air that is lost to radiative processes (mostly bremsstrahlung)

$k_{AK}$: Is a correction factor for attenuation and scatter from a Co-60 build-up cap \((k_{AK} = 1.005\text{ was used both for Ir}-192\text{ and Co}-60)\)

$k_v$: Correction for the finite volume of the measuring probe (following the recommendations by Kondo and Randolph\cite{20} the 1 cm³ thimble chamber 23331 (1.0 cm³) has a $k_v = 1.0010$ for source-chamber distances between 15 cm and 25 cm and $k_v = 1.0000$ for source-chamber distances $\geq 30$ cm)

$k_{scatt}$: Correction for scatter from surrounding objects (floor, walls, set-up, etc.)

$k_{scatt} = (M - M_{scatt})/M$ with $M = \text{reading without scatter absorber}, M_{scatt} \text{reading with absorber}$

$N_w$: Calibration factor of ionization chamber in terms of absorbed dose to water

$M$: reading in nC

Measurement of reference air kerma rate with a thimble ionization chamber free in air following AAPM Report 41:

Reference air kerma rate \(K_R\) is determined following the equation\cite{12}:

\[
K_R = (1/(1 - g_a)) k_{AK} (W/e)_{air} k_{w \rightarrow a} k_{v} k_{A} k_{P} k_{S} k_{scatt} N_w [\text{mGy/}nC] M [nC]
\]

where

\[(W/e)_{air} = 33.97 \text{ J/C} = 8.76 \text{ mGy/R}\text{ is the ionization energy of dry air}\]

$k_v$: Correction factor for recombination losses in the ionization chamber (named “correction for the collection efficiency at calibration A ion” or “correction for the collection
efficiency at the time of the study \( P_{\text{eff}} \) in AAPM Report 41.

\[ k_{\text{scatt}}: \text{Correction for room scatter (in AAPM Report 41:} \text{“room scatter correction } P_{\text{RS}} \text{”)}

\[ N_i: \text{Calibration factor of ionization chamber in terms of exposure. } N_i \text{ for Ir-192 was calculated by the equation given in Table 3 (as recommended by IAEA-TECDOC 1274).}

\[ M: \text{Reading in nA}

The “exposure gradient (displacement) correction } P_{\text{grad}} \text{“ recommended in AAPM Report 41 is set to 1.0 in this work.}

**Measurement of reference air kerma rate with a well-type chamber following DIN 6809-2 and IAEA-TECDOC 1274:**

Set-up for the well chamber measurements is identical in both protocols [Figure 3]. The chamber was positioned at large distance from any wall or large object in order to reduce scatter radiation as far as possible. The measurements were performed in a dedicated source holder for each type of source (for the Nucletron Ir-192 source: T33002.1 and for the Bebig Co-60 source: T3304.1, both PTW Freiburg) at the dwell position in the chamber producing the maximal ionization current (the “sweet spot”). In the measurements the identical source holder (type and serial no.) must be used as for calibration of the well chamber. Measurements were performed in current mode of the electrometer after achieving a constant current.

Reference air kerma rate \( K_R \) is determined following the equation

\[ K_R [\text{mGy/h}] = k_p k_s k_N w [\text{mGy/h/nA}] M [\text{nA}]

with

\[ k_s = 1/A_{\text{ion}}: \text{Correction factor for recombination losses in the well-type chamber}

\[ N_i: \text{Calibration factor of well-type chamber in terms of absorbed dose to water}

\[ M: \text{Reading in nA}

**Measurement of reference air kerma rate with a well-type chamber AAPM Report 41:**

In contrast to DIN 6809-2 and IAEA-TECDOC 1274, AAPM Rept. 41 requires a well-type chamber which is calibrated in terms of exposure.

Reference air kerma rate \( K_R \) is determined following the equation

\[ K_R [\text{mGy/h}] = (W/e)_w k_p k_s k_N w [\text{R/h/nA}] M [\text{nA}]

where:

\[ N_i: \text{Calibration factor of well-type chamber in terms of exposure}

\[ M: \text{Reading in nA}

Table 2 shows parameters and correction factors used in the calculation of air kerma rate from the readings. Additional factors have been described previously. The values of all factors were taken from literature. \[5, 6, 10, 12, 14-17\]

Usually, ionization chambers are not calibrated directly for Ir-192. The different protocols solve this problem by different methods.

DIN 6809-2 uses the calibration factor for Co-60 for both isotopes and corrects the Ir-measurements for differing radiation quality with a factor \( k_Q = 1.0 \). IAEA \[1\] and AAPM \[12\] recommend interpolating the Ir-192 calibration from calibration factors for 250 kV x-rays and Co-60 gamma radiation as shown in Table 3.

A number of corrections must be determined for the individual ionization chamber. Their calculation and values are listed in Table 4. The well-type chambers are individually calibrated for each isotope.

While DIN 6809-2 (Rept. 13) and IAEA-TECDOC 1274 give recommendations for all correction factors for Ir-192, some are missing in AAPM Rept. 41. None of the protocols gives any correction factors for Co-60. These were therefore taken from scientific literature \[15, 16, 18\]. Where no published factors were found, either the values recommended for Ir-192 by DIN 6809-2 or IAEA-TECDOC 1274, or where applicable, were set equal to 1 (AAPM Rept. 41).

**Results**

The sources were repeatedly measured on different days. On each day the measured reference air kerma rates were recalculated to the equivalent rate at the time of calibration as indicated in the source certificate. Then the differences between measured and certified air kerma rates were averaged separately for each protocol. The variance of the measurements additionally indicates the reproducibility of each method. Mean deviations from the certified calibration and the variation of the measurements are shown as fat bars in Figure 4, the error bars indicate the variation of repeated measurements.

All protocols and methods of measurement show agreement with the certified air kerma rates within maximally 1.2% for Ir-192 and 2.5% for Co-60.

Table 5 shows that generally the deviations of the measured from the certified air kerma rate are larger.
for Co-60 (maximum deviation $-2.5\%$) than for Ir-192 (maximum deviation 1.2\%). The smallest deviations ($<1\%$) are found in the measurements with the well-type chamber. The Ir-192 results of this work agree well with results in literature\cite{14,21}. Deviations are far below the uncertainties of $\pm 6\%$ for Co-60 (Amersham-Buchler/Bebig) or $\pm 5\%$ for Ir-192 (Nucletron) specified in the source certificates provided by the suppliers\cite{9}.

First measurements on Bebig Co-60 sources were published by Andrassy and Grundei in 2006\cite{15} and 2008\cite{16} after introduction of the new Bebig afterloader. In this work the authors also determined the Co-60 phantom calibration factor $k_{zp}$ for the Krieger PMMA phantom. These measurements also deviated from the certified values by $\pm 2\%$ and therefore confirm our measurements in the Krieger phantom where we obtained deviations of 1.6\%. Our Co-60 measurements free in air deviate from the certificate by 2.5\%, the well chamber measurements by 0.8\%.

**Discussion**

In the experiments, free in air the scatter radiation component was determined by a second measurement using a scattering block which was then subtracted from the measurement without absorber. The scatter contribution was dependent on the position of source and ionization chamber and their distance from any wall or massive object. For Ir-192 it amounted to around 2\% (corresponding to a correction factor $k_{scatt} = 0.98$) and for Co-60 around 4\% ($k_{scatt} = 0.96$).

For the measurements in the PMMA phantom and using the well-type chamber, scatter contributions can be neglected provided the distances to walls and massive objects are large enough (generally $>1.5\ m$).

Free in air measurements require a minimum ionization chamber volume of 1 cm$^3$.\cite{14} Whether or not a build-up cap should be used is discussed controversial in literature. DGMP Rept.13 and IAEA-TECDOC 1274 recommend the use of a Co-60 build up cap both for Co-60 and for Ir-192.

Different protocols recommend source-chamber distances between 10-30 cm\cite{4,5} and 1 m.\cite{3,12} At a distance in the region of 1 m the chamber signal can be very small and measuring times very large, so that statistical noise and dark currents can increase measurement uncertainty. On the other hand, at this distance positioning errors and the uncertainty of the effective measuring position of the probe contribute less to overall uncertainty. Generally, the positioning uncertainties must be reduced to a minimum. This can be achieved e.g., by use of a precise measuring jig (as in this work) or also by varying the position and determining the exact source chamber distance from the distance dependence of the reading using the method described by Goetsch\cite{22}.

The uncertainties in these measurements are summarized in Table 6. The uncertainties of any quantity were either taken from the specifications of the respective manufacturer, the recommendations in the protocols or calculated as standard deviations of repeated measurements. The total uncertainty is calculated as the root square sum of the individual uncertainties. These independently calculated total uncertainties for all three methods agree well with the best practice uncertainties ($k = 1$) as stated by AAPM Task Group No. 138\cite{23} for the measurement of $S_e$ in the clinic using a well-type chamber.

In the equations recommended by some protocols to calculate air kerma rate a number of corrections are missing. E.g., DGMP Rept.13 uses no corrections $k_A$ for recombination losses or $k_s$ for attenuation by the applicator. Especially applicator attenuation can require a considerable factor when measuring in a steel or titanium applicator. In this work attenuation factors $k_A = 1.0165$ and $1.0267$ for Ir-192 and Co-60, respectively were used. These factors were taken from recommendations by Bebig TPS HDRplus version 2.2\cite{24} and Baltas\cite{10}.

For calibration measurements on Ir-192 using an ionization chamber some protocols recommend to obtain two chamber calibrations (DIN 6809-2\cite{6}; Co-60 and 250 kV X-rays; AAPM TG 56\cite{25}: Cs-137 and 250 kV X-rays) in order to calculate the interpolated calibration factor for Ir-192. Since determination of $N_k$ by interpolation will add some increased uncertainty in the air kerma calibration factor for Ir-192, a direct calibration for Ir-192 is desirable as it is provided by the British NPL\cite{26} and the German PTB.\cite{27} These standard laboratories will provide Ir-192 calibrations in terms of reference air kerma rate.

### Table 5: Deviations of measured Air kerma rate from the source certificate value and measured relative uncertainties (in brackets) for different protocols

| Method                                          | DIN 6809-2 (1993) | IAEA-TECDOC-1274 (2002) | AAPM Report 41 (1993) |
|------------------------------------------------|------------------|-------------------------|-----------------------|
|                                                 | Ir-192(\%) | Co-60(\%) | Ir-192(\%) | Co-60(\%) | Ir-192(\%) | Co-60(\%) |
| Measurement with cylindrical chamber in cylindrical PMMA phantom | 1.1 (1.20) | 1.1 (0.35) | -0.4 (0.37) | -2.2 (0.18) | -0.5 (0.34) | -2.5 (0.19) |
| Free in air measurement with cylindrical chamber | 1.2 (0.37) | -2.2 (0.22) | 0.6 (1.06) | -0.8 (0.35) | 0.6 (1.06) | -0.8 (0.35) |
for well-type chambers, and for free complete measurement arrangements for free-in-air measurement (consisting of ionization chamber, source holder and measurement jig) or complete PMMA phantom arrangements (consisting of ionization chamber, source holder and phantom). Calibrations of other types of ionization chambers in terms of air kerma rate for Ir-192 are so far not available.

Well-type chambers have proven to be fast and precise measuring instruments. They are also used for source calibration by the manufacturers. In clinical use the PMMA phantom may have some advantages since it can also be used e.g., to check the calibration of in-vivo probes or for QA tests of the after loading machine. If one has no direct calibration of the phantom arrangement (as provided by PTB[27]), one needs to know the phantom calibration factor $k_p$. In some cases $k_p$ can be obtained from the manufacturer (or from literature), otherwise one needs to determine it by cross-calibration from a measurement of reference air kerma rate using one of the other methods. Calibration factors for the Krieger type PMMA phantom used in this work are available both for Ir-192 and for Co-60.

DGMP Report 13 provides guidance for dosimetry of Ir-192 sources for all three methods of measurement.

Table 6: Overview of influence quantities and their contributions to total uncertainty. Where not stated otherwise, uncertainties are taken from[10]

| Influence quantities | Source | Krieger phantom with PTW-M30013(%) | Free in air with PTW-M23331(%) | Well-type chamber(%) |
|---------------------|--------|------------------------------------|---------------------------------|---------------------|
| Distance Source - Chamber (SCD) | Krieger phantom: Approximation: 0.3 mm @ 80 mm SCD • 0.3/80 * 100% = 0.4% Free in air: Approximation: 1.0 mm @ 400 mm SCD • 1.0/400 * 100% = 0.3% Well-type chamber: Approximation: 0.2 mm @ 30 mm SCD • 0.2/30 * 100% = 0.6% |
| $N_w$ | Deviation of calibration certificate | 0.5 | 0.5 | 0.5 |
| $N_p$ | Stability of calibration factor | 0.2 | 0.2 | 0.2 |
| $k_p$ | Uncertainty of measured corrections factors | 0.1 | 0.1 | 0.1 |
| $\Delta k_p/k_p$ | $\Delta k_p = \Delta T/T + \Delta p/p$ | 0.5 | 0.5 | 0.5 |
| $k_r$ | Deviation of corrections factors | 1.0 | 1.0 | 1.0 |
| Dosimeter reading | Manual PTW-UNIDOS: Accuracy of current and charge measurement | 0.5 | 0.5 | 0.5 |
| Linearity deviation | Manual PTW-UNIDOS: Linearity uncertainty | 0.5 | 0.5 | 0.5 |
| Long time stability dosimeter/year | Manual PTW-UNIDOS: 0.1% per year => 5 years | 0.5 | 0.5 | 0.5 |
| Total uncertainty (Standard deviation): | | 1.6 | 1.5 | 1.6 |

Figure 3: Shows the measurements with the well chamber with the Nucletron After loader and an Ir-192-Source

Figure 4: Deviations from the certified calibration of Co-60 and Ir-192 sources in three protocols. The error bars indicate the variation of repeated measurements
(including measurements in the Krieger type PMMA phantom) following the German standard protocol DIN 6809-2 which is dated from 1993 and is outdated in some parts.

The international protocol IAEA-TECDOC-1274[1] and AAPM Report 41[2] give recommendations only for measurements free in air and for the well-type chamber. AAPM Report 41 report (from 1992) is outdated since it still recommends using an ionization chamber calibrated in exposure but is in principle still applicable provided one can obtain a calibration in exposure. This type of calibration has been replaced by calibration in terms of absorbed dose to water in most protocols, including the American AAPM TG 51 protocol for high energy photon and electron beams.[28] AAPM TG 56[29] recommends measuring Ir-192 source strength using instruments calibrated directly in terms of air kerma however gives no correction factors.

It is desirable to agree on an internationally accepted common protocol which describes all methods of calibration using the best available correction factors, and also giving recommendations for Co-60 sources, and possibly also for a number of other nuclides which may be available for high dose rate afterloading in the near future. A direct calibration of the chambers for Ir-192 compared to the interpolative method (uncertainty about 2%) showed an uncertainty of 0.8%,[29,30] According to AAPM TG 138,[31] the propagation of uncertainties from the various well-chamber measurements involved in the transfer of the source-strength standard to the clinic results in a minimum expanded uncertainty (k = 2) in $S_{\text{K,CLINIC}}$ of 2.56%. Therefore, in clinical practice it is recommendable to use the more precise direct calibration.

In the international co-operation EURAMET[31] several national standard laboratories have collaborated in the project JRP06 brachytherapy in which new standards for the calibration of brachytherapy sources are under development. Within this project methods are being developed to directly measure the absorbed dose to water surrounding brachytherapy isotopes including Ir-192 at distances of a few cm.[31-37] As a major result the project has obtained an improved value for the dose rate constant $\lambda$ reducing the uncertainty in source specification (in reference air kerma rate) from previously ±5% to around ±2% ($k = 2$).[37] Source specification directly in terms of absorbed dose to water is not planned. If this were the case the same methods of source verification could be used. With these standards it would however be necessary to determine new calibration factors for the instruments in terms of absorbed dose to water.

Dose calculations with such a specification could be performed in the same manner as today, since in the AAPM TG-43 formalism[12] the product is equal to the dose rate in water under reference conditions. The remaining formalism could be used without changes since all factors in the calculation are defined already in terms of absorbed dose to water.

**Conclusions**

Verification of source calibration of Co-60 HDR brachytherapy sources by the clinical user is feasible. Source strength for Co-60 sources can be measured with comparable uncertainty using the same instruments with the same dosimetry protocols as used for the more common Ir-192 sources. The correction factors to calculate air kerma rate from the reading of calibrated ionization chambers for Co-60 can be taken from literature. Since dose distributions for Co-60 are very similar to those for Ir-192,[11] Co-60 brachytherapy sources may be an attractive and cheaper alternative to the existing Ir-192 sources.

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