# Comparison BIPM.RI(I)-K8 of high dose-rate Ir-192 brachytherapy standards for reference air kerma rate of the VSL and the BIPM

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**Abstract**

A new key comparison of the standards for reference air kerma rate for $^{192}$Ir high dose rate (HDR) brachytherapy sources of the Dutch Metrology Institute (VSL), The Netherlands, and the Bureau International des Poids et Mesures (BIPM) was carried out at the VSL in May 2019. The comparison result, based on the calibration coefficients for a transfer standard and expressed as a ratio of the VSL and the BIPM standards for reference air kerma rate, is 0.9926 with a combined standard uncertainty of 0.0055.

## 1. Introduction

The Brachytherapy Standards Working Group (BSWG), created under the recommendation made by the Consultative Committee for Ionizing Radiation CCRI(I), proposed at their meeting of November 2005 to start a comparison of primary standards for reference air kerma rate (RAKR) of $^{192}$Ir. To meet the needs of the National Metrology Institutes (NMIs), a new ongoing key comparison was registered in the BIPM key comparison database (KCDB 2024) under the reference BIPM.RI(I)-K8. As no primary facility for brachytherapy is available at the BIPM, the measurements take place at the NMI using one of the two BIPM transfer standards, a NE 2571 thimble-type transfer ionization chamber or a well-type ionization chamber.

The Dutch Metrology Institute (VSL) took part in the comparison in May 2019, to update the previous comparison result of 2009 (Alvarez *et al.* 2014) published in the KCDB. This comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories.

The present comparison was run using only the thimble-type chamber and the comparison result is given in terms of the ratio of the calibration coefficients of the chamber determined at the VSL in the $^{192}$Ir radiation beam and at the BIPM in the $^{60}$Co reference radiation beam, the latter corrected by a calculated factor to account for the energy dependence of the NE 2571 chamber type between $^{60}$Co and $^{192}$Ir (Mainegra-Hing *et al.* 2006).

The comparison result, approved by the CCRI, is analysed and presented in terms of degrees of equivalence for entry in the BIPM key comparison database.

## 2. Characteristics of the transfer instrument

The transfer instrument, belonging to the BIPM, used to undertake the comparison, was a NE 2571 thimble chamber. The main characteristics of the thimble chamber are listed in Table 1.

**Table 1. Characteristics of the BIPM transfer chamber**

| Characteristic/Nominal values | | NE 2571-2806 |
|---|---|---|
| Dimensions | Inner diameter / mm | 6.3 |
| | Cavity length / mm | 24.0 |
| | Wall mass thickness / g cm$^{-2}$ | 0.065 |
| | Tip to reference point / mm | 13.0 |
| | Bottom to reference point / mm | - |
| Electrode | Length / mm | 21.0 |
| | Diameter / mm | 1.0 |
| Air cavity | Volume / cm$^3$ | 0.7 |
| Wall | Material | Graphite |
| | Density / g cm$^{-3}$ | 1.7 |
| Build-up cap | Material | Delrin |
| | Thickness / g cm$^{-2}$ | 0.551 |
| Voltage applied to outer electrode / V | | –250 |

## 3. Determination of the VSL reference value

As the VSL has no primary standard for high dose-rate (HDR) $^{192}$Ir brachytherapy sources, the reference air kerma rate RAKR is determined using a secondary standard NE 2571 ionization chamber. The main characteristics are listed in Table 1. The determination of the calibration coefficient for $^{192}$Ir is based on an interpolation between the air kerma calibration coefficients for the CCRI(I) 250 kV x-ray beam (the mentioned quality is described in Kessler and Burns (2024), where the primary standard is a free-air chamber, and a $^{137}$Cs γ-ray beam, where the primary instrument is a graphite-walled cavity chamber, using the method described by Petersen *et al.* (1994) and van Dijk *et al.* (2004). To obtain the air kerma calibration coefficient $N_K$ for $^{192}$Ir, $N_K^{\text{Ir-192}}$, each $^{192}$Ir spectral line is treated individually; the air kerma calibration coefficient is obtained for each spectral line by interpolation on the ionization chamber energy response curve and weighting them according to the intensity of each spectral line. The $^{192}$Ir spectrum was taken from the DDEP database (Browne 2003). The calibration coefficient $N_K^{\text{Ir-192}}$was also determined using the microSelectron HDR $^{192}$Ir spectrum; the agreement of the calibration coefficients evaluated using these two spectra was better than 2 parts in $10^4$.

The calibration coefficient for the secondary standard ionization chamber thus obtained was compared to the one obtained using a linear (unweighted) interpolation between the CCRI(I) 250 kV x-ray and $^{137}$Cs beams and to an interpolation based on three beam qualities using the CCRI(I) 250 kV x-ray quality, an ISO N-250 x-ray quality and $^{137}$Cs. From this comparison, it was concluded that an additional uncertainty of 3.7 parts in $10^3$ has to be added in the evaluation of the $N_K^{\text{Ir-192}}$ uncertainty to cover the differences between the three interpolation methods used (de Pooter 2023).

The RAKR is determined using the expression

$$\dot{K}_R = N_K^{\text{Ir-192}} I_{\text{Ir-192}} (d/(2.d_{\text{ref}}))^2 k_{\text{sc}} k_{\text{att}} k_{\text{rn}} k_{\text{dec}} k_{\text{s}} k_{\text{st}} k_{\text{pol}} \quad (1)$$

where

| | |
|---|---|
| $\dot{K}_R$ | is the RAKR at the chosen reference time of the comparison, |
| $N_K^{\text{Ir-192}}$ | is the secondary standard calibration coefficient for $^{192}$Ir determined using the interpolation method |
| $I_{\text{Ir-192}}$ | is the average ionization current measured with the source positioned at the dwell position corresponding to the maximum chamber response (sweet spot) in both catheters (see Figure 1), corrected for pressure and temperature $k_{p,T}$ |
| $d$ | is the average distance from the centre of the chamber to the centre of the two catheters |
| $d_{\text{ref}}$ | is the reference distance of 1 m |
| $k_{\text{sc}}$ | is the correction factor for scatter radiation from the irradiation room walls, equipment and the jig at the point of measurement |
| $k_{\text{att}}$ | is the correction factor for attenuation of the polystyrene catheter and the air column between the source and the ionization chamber |
| $k_{\text{rn}}$ | is the correction factor for non-uniformity of the radiation field at the point of measurement |
| $k_{\text{dec}}$ | is the correction factor for the decay of the $^{192}$Ir source since the reference date, using the half-life of 73.827 d (Woods *et al.* 1992) |
| $k_{\text{s}}$ | is the correction factor for ion recombination |
| $k_{\text{st}}$ | is the correction factor for the scatter from the secondary standard stem |
| $k_{\text{pol}}$ | is the correction factor for the polarity effect |

Since the last comparison in medium-energy x-rays (Burns *et al*. 2016), the VSL introduced some changes in the determination of air kerma using the free-air chamber due to the re-evaluation of Monte Carlo calculated correction factors, air attenuation correction factors and the implementation of ICRU 90, resulting in a decrease of 4.6 parts in $10^3$ of the air kerma rate determination for the quality used for the interpolation method.

The VSL air kerma determination in the $^{137}$Cs γ-ray beams has been updated due to small changes in the constants air density, *g* factor, polarity and recombination correction, and due to the implementation of ICRU 90, resulting in a reduction of 6.9 parts in $10^3$ of the air kerma rate determination. Considering these changes, the $N_K^{\text{Ir-192}}$ has been reduced by 5.7 parts in $10^3$.

The VSL standards have been compared against the BIPM primary standards in medium-energy x-rays and $^{137}$Cs γ-rays, and their main characteristics are described in the corresponding comparison reports (Burns *et al.* 2016, Kessler *et al.* 2016). These comparisons precede the changes adopted for air density, *g* factor and the implementation of the ICRU 90.

The main characteristics of the VSL $^{192}$Ir source are listed in Table 2.

*Ambient conditions*

The ionization current for each chamber is corrected to the reference conditions of 293.15 K and 101.325 kPa; relative humidity is controlled at (50 ± 5) % and no humidity correction is applied.

**Table 2. Characteristics of the VSL $^{192}$Ir source**

| | |
|---|---|
| After-loader unit | Nucletron MicroSelectron |
| Manufacturer of source | Mallinckrodt Medical BV |
| Source type | MicroSelectron V2, model 105.002, sn D36P9158 |
| Estimated activity of source | 456 GBq at 10/04/2019 03:43 CET |
| Capsule dimensions | 0.9 mm diameter and 4.5 mm length |
| Capsule material | Solid iridium |
| Source pellet dimensions | 0.6 mm diameter and 3.5 mm length |

## 4. Determination of the BIPM reference values

The BIPM does not possess an $^{192}$Ir source. The reference value for the thimble chamber used to evaluate the comparison result is based on measurements performed in the $^{60}$Co γ-ray beam, with supporting measurements in the CCRI(I) 250 kV x-rays.

The NE 2571 is calibrated periodically at the BIPM in the $^{60}$Co γ-ray beam, under the reference conditions described by Kessler and Burns (2024). The chamber is also calibrated periodically in the CCRI 250 kV x-ray beam to verify that its response at lower energies remains stable.

The calibration coefficient of the thimble chamber $N_{K,\mathrm{BIPM}}^{\mathrm{th}}$ for $^{192}$Ir is derived from the calibration coefficient determined in the BIPM $^{60}$Co γ-beam and a calculated correction factor $k_{\mathrm{en}}$ to take into account the energy dependence of this type of ionization chamber (Mainegra-Hing *et al.* 2006):

$$N_{K,\mathrm{BIPM}}^{\mathrm{th}} = N_{K,\mathrm{BIPM}}^{\mathrm{th,Co\text{-}60}} k_{\mathrm{en}} \quad (2)$$

Following the recommendations of the ICRU 90, the value for $k_{\mathrm{en}}$ has been re-evaluated by Burns and Kessler (2018); the updated value is 1.0015, with an estimated relative standard uncertainty of 1.5 parts in $10^3$ (the statistical standard uncertainty of the calculated value is 6 parts in $10^4$).

The BIPM mean values for the thimble chamber made around the period of the comparison are compared to the long-term value to verify the stability of the chamber. The long-term reproducibility in the BIPM $^{60}$Co beam is less than 1 part in $10^4$ in relative value (and 3 parts in $10^4$ for the 250 kV x-ray beam). Considering the long-term stability for the $^{60}$Co beam and the 250 kV x-ray beam an uncertainty of 2 parts in $10^4$ is included in the BIPM uncertainty budget.

## 5. Comparison procedure

The calibration coefficient $N_{K,\mathrm{VSL}}^{\mathrm{th}}$ for the BIPM thimble chamber at the VSL is given by

$$N_{K,\mathrm{VSL}}^{\mathrm{th}} = \frac{\dot{K}_{R,\mathrm{VSL}}}{I_{\mathrm{VSL}}\,(d/(2\cdot d_{\mathrm{ref}}))^2 k_{sc} k_{att} k_{rn} k_{dec} k_s k_{st}} \quad (3)$$

where $\dot{K}_{R,\mathrm{VSL}}$ is the VSL reference air kerma rate and $I_{\mathrm{VSL}}$ is the ionization current of the BIPM thimble chamber measured by the VSL; the correction factors are the same as defined in section 3. The relative standard uncertainty of the mean ionization current was estimated to be 2 parts in $10^4$ (two calibrations; for each calibration, three series of 8 measurements with source repositioning, as described below).

Determination of the BIPM calibration coefficient is described in Section 4. The chamber was calibrated before and after the measurements at the VSL; the relative standard uncertainty of the mean is taken to be 2 parts in $10^4$.

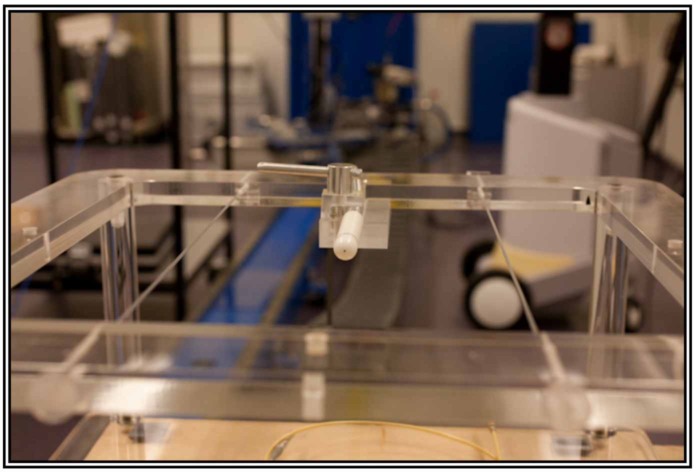
The ionization current in each case is corrected for the influence factors described below.

*Positioning*

At the BIPM, the BIPM thimble chamber is positioned with the stem perpendicular to the beam direction and with the appropriate marking on the stem (engraved line) facing the source; the build-up cap being used for both $^{60}$Co and 250 kV x-rays.

At the VSL, the BIPM thimble chamber is set up at the centre of the irradiation jig between two catheters that are each at a nominal distance of 10 cm from the chamber, as illustrated in Figure 1, and with the appropriate marking on the stem (engraved line) in the upward direction. The required longitudinal position of the source in both catheters relative to the ionization chamber was determined by stepping the source in small steps and measuring the current as a function of the source position. The required position was determined by calculating the maximum of the parabolic fit to this data. At this position, the current measured with the source in both catheters is averaged, reducing the uncertainty related to positioning. A set of at least three runs with repositioning of the source in between was made for each catheter.

**Figure 1. Set-up for the NE 2571 thimble chamber**



The NE 2571 thimble chamber in the VSL irradiation jig, equidistant from each lateral source position**.**

*Applied voltage and polarity*

At the BIPM, a collecting voltage of 250 V (negative polarity) is applied to the outer electrode of the chamber at least 30 min before any measurements are made. At the VSL, a collecting voltage of 250 V (positive polarity) is applied to the central electrode of the chamber at least 30 min before any measurements were made. Consequently, no corrections were applied at either laboratory for the polarity effect.

*Volume recombination*

Volume recombination is negligible at dose rates less than 15 mGy s$^{-1}$ for the chamber at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories. Consequently, no correction for recombination was applied at either laboratory.

*Charge and leakage measurements*

At the BIPM, the charge $Q$, collected by the transfer instrument is measured using a Keithley electrometer, model 642. The radiation source is operational during the entire exposure series and the charge is collected for the appropriate, electronically controlled, time interval.

At the VSL, the charge collected is measured similarly with a Keithley model 6517B electrometer.

At the BIPM, pre-irradiation was for at least 30 min (≈ 10 Gy) before any measurements were made and similarly at the VSL the chamber was pre-irradiated with at least 10 Gy. The measured ionization current was corrected for the leakage current at both laboratories. This correction was less than 1 part in $10^4$ in relative value at the BIPM and less than 1 part in $10^3$ at the VSL; the latter value being reproducible at the 1 part in $10^4$ level.

*Ambient conditions*

During the measurements, the air temperature was stable to better than 0.05 °C at both laboratories. The measurements are normalized to 293.15 K and 101.325 kPa. Relative humidity is controlled at (50 ± 5) % at both laboratories. Consequently, no correction for humidity is applied to the measured ionization current.

*Radial non-uniformity correction*

At the BIPM, the correction applied to the ionization current for the radial non-uniformity would only be 1.0002 for the transfer instrument, with an uncertainty of 2 parts in $10^4$. However, for this comparison, no correction for radial non-uniformity is made at the BIPM. At the VSL, no non-uniformity correction is applied as the BIPM transfer instrument is of the same type as the secondary standard used to calibrate the HDR $^{192}$Ir source and the radial non-uniformity correction should cancel in evaluating the calibration coefficient at the VSL. An uncertainty of 2 parts in $10^4$ is included in the VSL uncertainty budget to account for possible variations of the beam uniformity due to different positions of the chambers.

*Stem and room scatter*

Since the BIPM thimble chamber transfer instrument is of the same type as the secondary standard used at the VSL to calibrate the HDR $^{192}$Ir source, the stem and room scatter corrections cancel in evaluating the calibration coefficient. An uncertainty contribution of 4 parts in $10^4$ is added to account for the variation in scatter correction determinations in the last 10 years.

## 6. Results of the comparison

The individual calibration coefficients of the thimble chamber will not be disclosed as this transfer chamber will be calibrated by other NMIs participating in this ongoing comparison.

The comparison result is expressed as the ratio of the calibration coefficients of the thimble chamber determined at both laboratories,

$$R_{K,\mathrm{VSL}}^{\mathrm{th}} = N_{K,\mathrm{VSL}}^{\mathrm{th}} \big/ N_{K,\mathrm{BIPM}}^{\mathrm{th}} \qquad (4)$$

in which the average value of measurements made at the BIPM before and after those made at the VSL is compared with the mean of the measurements made at the VSL. For the VSL, the comparison result $R_K^{\mathrm{th}}$ is 0.9926.

## 7. Uncertainties

The uncertainties associated with the calibration of the thimble chamber at the BIPM are listed in Table 3.

The uncertainties associated with the determination of $\dot{K}_R$ and $N_{K,\mathrm{VSL}}^{\mathrm{th}}$ at the VSL are listed in Tables 4 and 5.

**Table 3. Uncertainties associated with the thimble chamber calibration at the BIPM**

| Relative standard uncertainty | $u_{iA}$ | $u_{iB}$ |
|---|---|---|
| $^{60}$Co air kerma determination $K$ | 0.0002 | 0.0013 |
| Ionization current $I_{th}$ | 0.0001 | 0.0002 |
| Positioning | 0.0001 | – |
| Radial non-uniformity | – | 0.0002 |
| Long-term stability | 0.0002 | – |
| Energy dependence $k_{en}$ | – | 0.0015 |
| $N_{K,\mathrm{BIPM}}^{\mathrm{th}}$ for $^{192}$Ir | 0.0003 | 0.0020 |

$u_{iA}$ represents the relative standard uncertainty estimated by statistical methods, type A
$u_{iB}$ represents the relative standard uncertainty estimated by other means, type B

**Table 4. Uncertainties associated with the reference air kerma rate determination at the VSL**

| Relative standard uncertainty | $u_{iA}$ | $u_{iB}$ |
|---|---|---|
| Calibration coefficient of the standard $N_K^{\mathrm{Ir\text{-}192}}$ | 0.0005 | 0.0048 |
| Ionization current $I_{VSL}$ | 0.0002 | 0.0004 |
| Decay correction $k_{dec}$ | – | < 0.0001 |
| Lateral distance $d$ | – | 0.0011 |
| Radial non-uniformity correction $k_{rn}$ | – | 0.0002 |
| Scatter correction $k_{scatt}$ | – | 0.0004 |
| Attenuation correction $k_{att}$ | – | 0.0010 |
| Stem scatter correction $k_{stem}$ | – | 0.0003 |
| Ion recombination correction $k_s$ | – | 0.0002 |
| Longitudinal position | – | 0.0002 |
| RAKR $\dot{K}_R$ for $^{192}$Ir | 0.0005 | 0.0051 |

**Table 5. Uncertainties associated with the thimble chamber calibration at the VSL**

| Relative standard uncertainty | $u_{iA}$ | $u_{iB}$ |
|---|---|---|
| $\dot{K}_R$ for $^{192}$Ir | 0.0005 | 0.0051 |
| *Calibration of the transfer chamber* | | |
| ionization current transfer chamber | 0.0002 | 0.0004 |
| Decay correction $k_{dec}$ | – | < 0.0001 |
| Lateral distance $d$ | – | 0.0011 |
| Radial non-uniformity correction $k_{rn}$ | – | 0.0002 |
| Scatter correction $k_{scatt}$ | – | 0.0004 |
| Attenuation correction $k_{att}$ | – | 0.0010 |
| Stem scatter correction $k_{stem}$ | – | 0.0003 |
| Ion recombination correction $k_s$ | – | 0.0002 |
| Longitudinal positioning | – | 0.0002 |
| $N_{K,\mathrm{VSL}}^{\mathrm{th}}$ | 0.0006 | 0.0053 |

Most of the uncertainties listed in Tables 4 and 5 (correction factors) are correlated as the VSL standard used to determine $\dot{K}_R$ and the transfer chamber under calibration are of the same type.

From the Tables 3 and 5 and removing correlations, the combined standard uncertainty $u_c$ for the comparison result $R^{\text{th}}_{K,\text{VSL}}$ is 5.5 parts in $10^3$.

## 8. Discussions

Since 2019 and following the decision of the CCRI(I), the BIPM and the participating laboratories started to implement the recommendations of the ICRU 90. Some laboratories have implemented also some improvements to their standards and the resulting changes adopted by the NMIs to update the comparison results are summarised in Table 6. New comparison results after the implementation of the ICRU 90 are also included in the table.

**Table 6. Comparison results updated with the changes implemented by the NMIs**

| Year of participation | NMI | NMI change | Comparison result pre-2019 | Updated comparison result |
|---|---|---|---|---|
| | BIPM | 0.9913 | | |
| 2009 | VSL [a] | 0.9943 | 0.9873 | 0.9903 |
| 2010 | NPL [a] | 1.0029 | 0.9989 | 1.0106 |
| 2011 | PTB [a] | 0.9883 | 1.0003 | 0.9973 |
| 2014 | NRC [a] | 0.9955 | 0.9966 | 1.0009 |
| 2015 | NMIJ [b] | 0.9917 | 1.0036 | 1.0040 |
| New participation in the BIPM.RI(I)-K8 | | | | New comparison result |
| 2019 | VSL [a] | | | 0.9926 |
| 2022 | NPL [b] | | | 1.0045 |
| 2023 | PTB [b] | | | 1.0022 |

[a] results obtained using the thimble chamber

[b] results obtained using the well-type chamber

## 9. Degrees of equivalence

For each NMI $i$ having a comparison result $R_{K,i}$ (denoted $x_i$ in the KCDB) with combined standard uncertainty, $u_i$, the degree of equivalence with respect to the key comparison reference value is given by a pair of terms:

the relative difference $D_i = (N_{K_R,\text{NMI}i} - N_{K_R,\text{BIPM}})/N_{K_R,\text{BIPM}} = R_{K,i} - 1$ (5)

and its expanded uncertainty $U_i = 2\ u_i$. (6)

The results for $D_i$ and $U_i$, are expressed in mGy/Gy. Table 7 gives the values for $D_i$ and $U_i$ for the NMIs that have participated to date, taken from the KCDB of the CIPM MRA (1999) and this report. These data are presented graphically in Figure 2.

**Table 7.** **Degrees of equivalence**

For each laboratory $i$, the degree of equivalence with respect to the key comparison reference value is the difference $D_i$ and its expanded uncertainty $U_i$. Tables formatted as they appear in the BIPM key comparison database

BIPM.RI(I)-K8

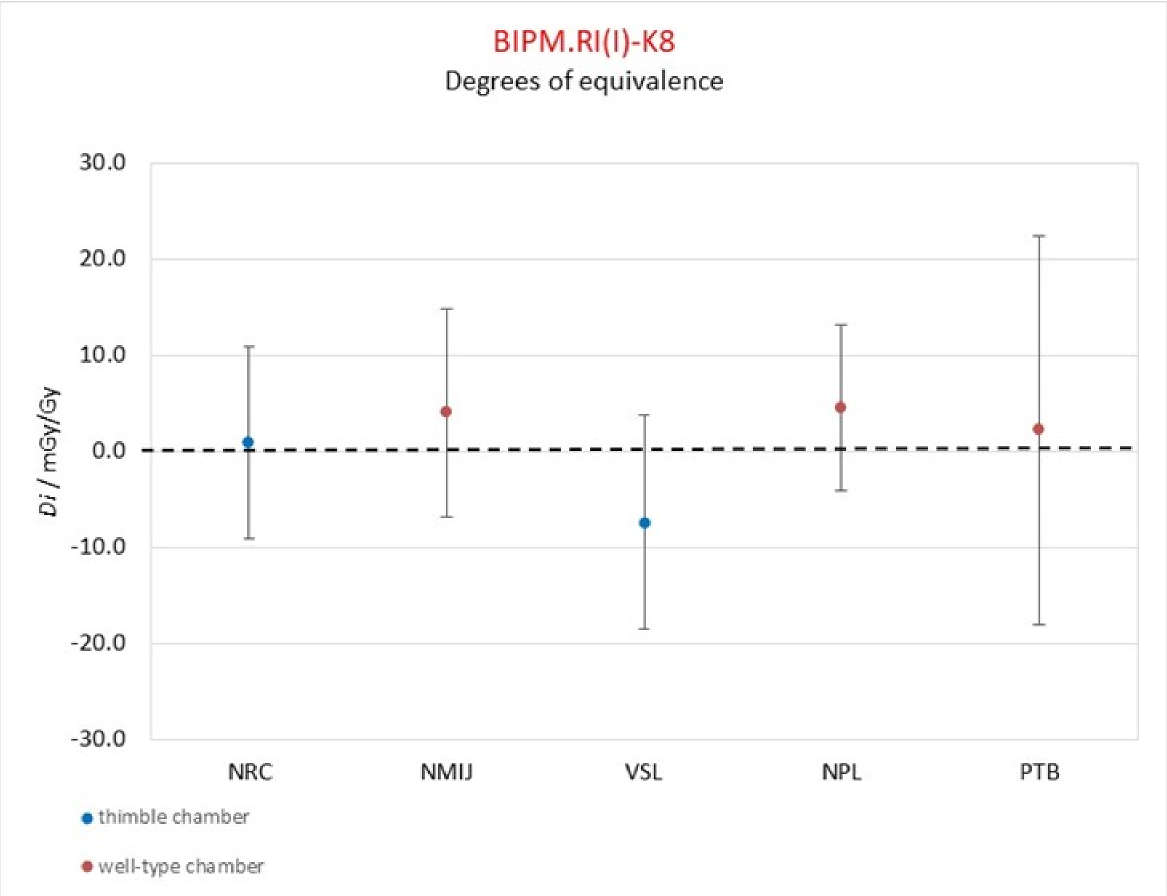
| | Lab $i$ | $D_i$ | $U_i$ |
|---|---|---|---|
| | | /(mGy/Gy) | |
| a) | NRC | 0.9 | 10.0 |
| b) | NMIJ | 4.0 | 10.8 |
| a) | VSL | -7.4 | 11.0 |
| b) | NPL | 4.5 | 8.6 |
| b) | PTB | 2.2 | 20.2 |

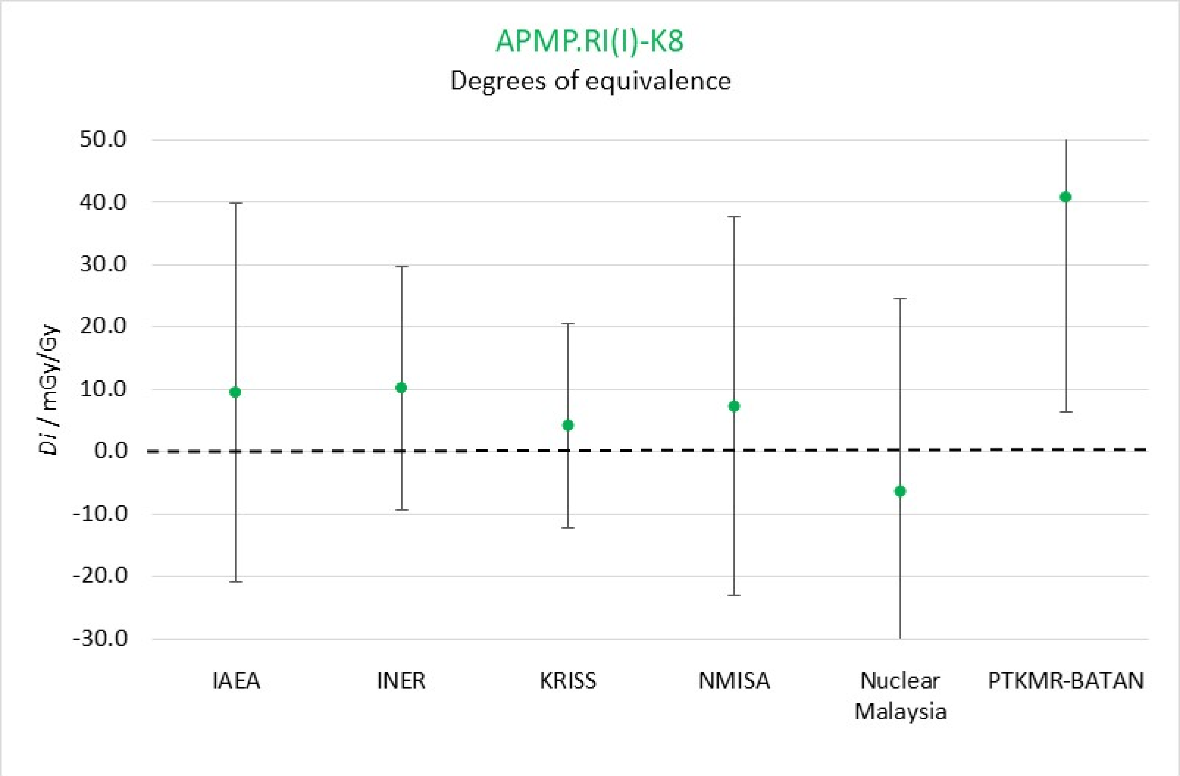
APMP.RI(I)-K8

| Lab $i$ | $D_i$ | $U_i$ |
|---|---|---|
| | /(mGy/Gy) | |
| IAEA | 9.4 | 30.4 |
| INER | 10.1 | 19.6 |
| KRISS | 4.2 | 16.4 |
| NMISA | 7.3 | 30.4 |
| Nuclear Malaysia | -6.4 | 30.8 |
| PTKMR-BATAN | 40.8 | 34.4 |

[a] results obtained using a thimble-type chamber
[b] results obtained using a well-type chamber

**Figure 2.** **Graph of the degrees of equivalence with the KCRV**






## 10. Conclusion

The VSL standard for the reference air kerma rate for $^{192}$Ir gamma radiation compared with the BIPM reference value gives a comparison result of 0.9926 with a combined standard uncertainty $u_c$ of 0.0055, which is in agreement with the previous comparison when updated by the changes adopted by each laboratory.

The degrees of equivalence with the other participants in the BIPM.RI(I)-K8 comparison are within the expanded uncertainty.

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