Comparison BIPM.RI(I)-K8 of high dose-rate ^{192}Ir brachytherapy standards for reference air kerma rate of the LNE-LNHB and the BIPM

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Abstract

An indirect comparison of the standards for reference air kerma rate for ^{192}Ir high dose rate (HDR) brachytherapy sources of the Laboratoire National Henri Becquerel (LNE-LNHB), France, and of the Bureau International des Poids et Mesures (BIPM) was carried out at the LNE-LNHB in May 2024. The comparison result, based on the calibration coefficients for a transfer standard and expressed as a ratio of the LNE-LNHB and the BIPM standards for reference air kerma rate, is 0.9990 with a combined standard uncertainty of 0.0071.

1. Introduction

The Brachytherapy Standards Working Group (BSWG(I)), 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 Laboratoire National Henri Becquerel (LNE-LNHB) took part in the comparison in May 2024. The comparison was carried out during the process of implementing the recommendations of the ICRU Report 90 (ICRU 2016) at the LNHB. The comparison result is evaluated considering the implementation of the ICRU 90 at both laboratories.

As the LNE-LNHB provides traceability for HDR ^{192}Ir sources calibrating only well-type chambers, the present comparison was run using only the BIPM well-type chamber and the result is given in terms of the ratio of the calibration coefficient determined at the LNE-LNHB and the reference value used by the BIPM. The BIPM reference value is the mean of the calibration coefficients determined by the BIPM during the comparisons with the NMIs that have participated calibrating the thimble chamber (VSL, NPL, PTB and NRC) during the period 2009-2014 (KCDB 2024).

The long-term stability of the well chamber is established by measurements at the BIPM using a ^{137}Cs source.

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 Standard Imaging HDR 1000 Plus well chamber. The main characteristics of the transfer instrument are listed in Table 1.

Table 1. Characteristics of the BIPM transfer chamber

Characteristic/Nominal values		Standard Imaging HDR 1000 Plus	Standard Imaging Insert 70010
Dimensions	Inner diameter / mm	102	35
	Cavity length / mm	156	121
	Bottom of insert to reference point / mm	50 (sweet-spot)	
Air cavity	Volume / cm^3	245	
Voltage applied	Polarity to outer electrode / V	+ 300	

3. Determination of the LNE-LNHB reference value

Description of the standard

The LNE-LNHB 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 2.

Table 2. Characteristics of the LNE-LNHB secondary standard

Nominal values		NE 2571-3169
Chamber	Outer diameter / mm	7.0
	Outer length / mm	24.5
Electrode	Diameter / mm	1.0
	Length / mm	20.6
Cavity	Measuring volume / cm^3	0.7
Wall	Thickness / mm	0.36
	Material	graphite
	Density / g cm^{-3}	1.7
Voltage applied to outer electrode / V		+300

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 (Burns *et al*. 2020), and for a ^{137}Cs γ-ray beam, where the primary determination of the air kerma rate is based on a set of six graphite-walled primary standard cavity chambers (Delaunay *et al*. 2010).

For the interpolation between 250 kV x-rays and ^{137}Cs, a linear dependence is considered between the reciprocal of the calibration coefficients as a function of the effective energy of the beam. The effective energy is considered to be the average energy of the emission spectrum weighted by the fraction of kerma of each energy component:

$$E_{\mathrm{Eff}} = \sum_i \frac{\dot{K}(E_i)}{\dot{K}} E_i \qquad (1)$$

under the assumption of discrete emission lines; or more generally:

$$E_{\text{Eff}} = \frac{\int_0^{E_{\max}} E\,\frac{dK_{\text{air}}(E)}{dE}\,dE}{\int_0^{E_{\max}} \frac{dK_{\text{air}}(E)}{dE}\,dE} \tag{2}$$

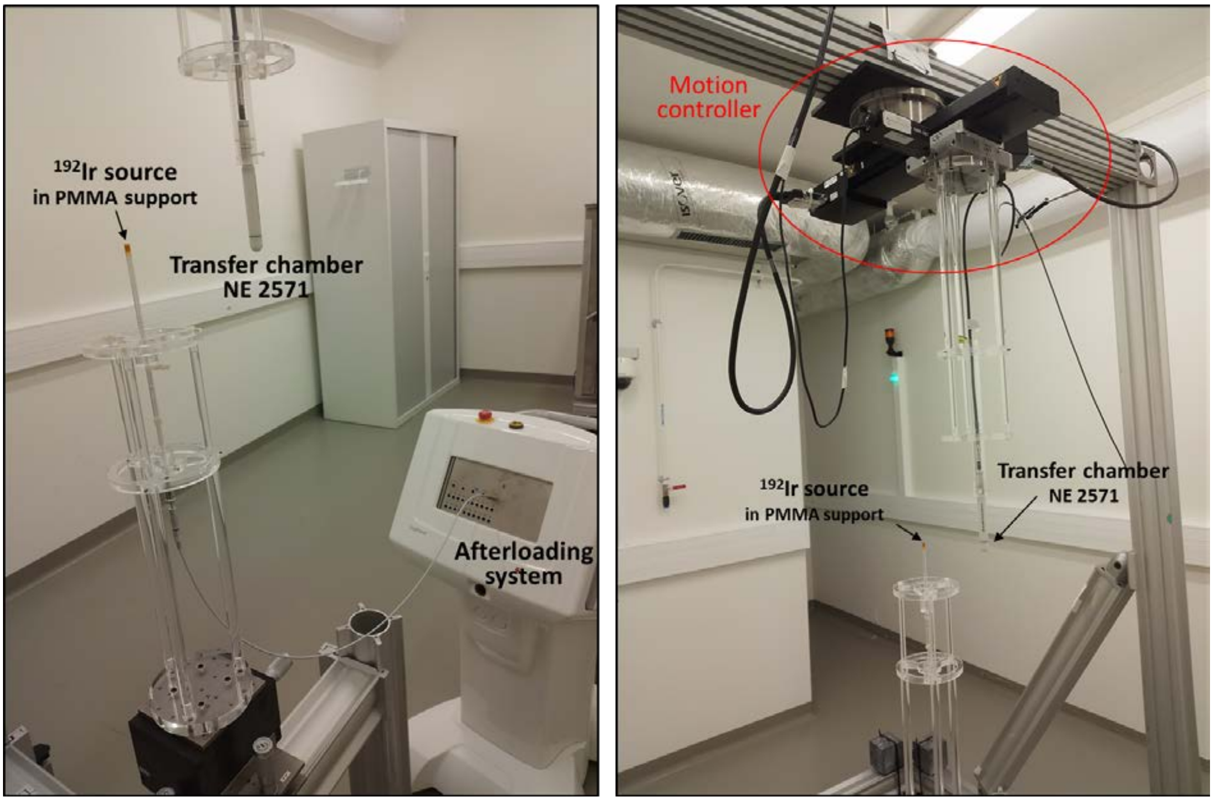
where $dK_{air}(E)$ is the air kerma contribution from emitted particles whose energy is between E and $E+dE$. The energy distribution of kerma was calculated from the energy distribution of fluence, obtained from simulation in the case of the ^{192}Ir and ^{137}Cs sources and from experimental measurements in the case of the 250 kV x-ray beam.

The effective energies thus obtained and used for the interpolation are 135.1 keV, 397.3 keV and 628.9 keV for the 250 kV x-ray, ^{192}Ir and ^{137}Cs beams, respectively.

Determination of the RAKR

The experimental set-up to determine the reference air kerma rate is shown in Figure 1.

Figure 1. Set-up for the calibration of HDR brachytherapy source



(a) (b)

The source is projected into a PMMA support, and the secondary standard is placed at a distance of 15 cm from the centre of the source support, sufficiently far from the walls of the room to minimize scatter radiation. A Newport motion controller ESP301 calibrated at the LNE is used to position the secondary standard at the measuring distance d.

The RAKR is determined using the equation

$$\dot{K}_R = N_K\, I(d)\, \left(\frac{d}{d_{\text{ref}}}\right)^2 k_{\text{dec}}\, k_{\text{att}} k_{\text{rn}}\, k_{\text{sc}} \tag{3}$$

where

$\dot{K}_R$	is the RAKR at the time of the comparison,
N_K	is the secondary standard calibration coefficient for ^{192}Ir determined using the interpolation method
$I(d)$	is the current measured at the distance d, corrected by leakage and normalized to the reference conditions 293.15 K and 101 325 Pa
d_{ref}	is the reference distance of 1 m
k_{dec}	is the correction factor for the decay of the ^{192}Ir source
k_{att}	is the combined correction factor for the air attenuation between source and chamber and the attenuation in the source support.
k_{rn}	is the correction factor for the non-uniformity of the radiation field at the point of measurement.
k_{sc}	is the correction factor for contributions from scattered photons to the chamber response.

Decay correction k_{dec}

The decay correction factor is calculated using the half-life of 73.827 with u_c = 0.013 days (Bé *et al.* 1999); it corrects for the source decay from the source calibration date 2024-04-03, 12:00 UTC to the reference date 2024-05-02, 12:00 UTC chosen for the comparison.

Air and source support attenuation k_{att}

The correction factor for the air attenuation between the source and the chamber and the attenuation of the photons emitted from the HDR ^{192}Ir source by the source holder was obtained using Monte Carlo simulations for the source spectrum.

Radial non-uniformity correction k_{rn}

The correction for the non-uniformity of the beam across the chamber volume at the measuring distance is calculated using the expression recommended in the IAEA Technical Reports TECDOC IAEA N°1079 and 1274.

Scatter radiation k_{sc}

The scatter radiation correction is determined from current measurements at different source-to-chamber distances between 10 and 22 cm. The current measured by the chamber $I(d)$ at different distances d can be expressed as

$$I(d) = I_{\text{sc}} + I_p \cdot \frac{1}{d^2} \cdot \frac{1}{k_{\text{rn}}(d) \cdot k_{\text{att}}} \qquad (4)$$

where I_{sc} is the scatter component, assumed to be constant at different distances and I_{p} is the current due only to primary radiation, corrected by radial non uniformity $k_{\text{rn}}(d)$ for each distance and beam attenuation k_{att}, the latter calculated using Monte Carlo methods for each distance. From the Monte Carlo calculations, it was deduced that k_{att} can be considered, well within the uncertainties of 1.9 parts in 10^3, as a constant value for all the distances.

From a fit of the measured current $I(d)$ as a function of the distance d, the contribution of scattered radiation (I_{sc}) is obtained; the correction factor k_{sc} at a particular distance is given by

$$k_{\text{sc}}(d) = 1 - \frac{I_{\text{sc}}}{I(d)} \qquad (5)$$

Polarity correction k_{pol}

No correction for polarity effect is applied, as the secondary standard was calibrated applying the same polarizing voltage used for the calibration of the ^{192}Ir source.

Ion recombination k_s

For this type of chamber, volume recombination is negligible at kerma rates of a few Gy/h, and as the initial recombination is the same for all the beams, no correction for recombination is applied.

Distance and positioning

The source-to-detector distance (*d*) is controlled by means of a Newport motion controller ESP301 (Fig. 1b), calibrated by the LNE, allowing the positioning of the secondary standard at the reference distance with an estimated relative uncertainty of 3 parts in 10^4.

The non-centered position of the source inside the holder is determined from the ionization currents measured when the chamber is positioned at different angles around the source, keeping the same source holder-chamber distance in the transverse plane of the source. A fit to these data allows to calculate the displacement of the source inside the holder and apply a source-chamber distance correction.

The calibration coefficient values, the correction factors involved in the determination of the RAKR at the reference distance of 1 m and the associated uncertainties are given in Table 3.

Table 3. Calibration coefficients and correction factors with their relative standard uncertainties of the LNE-LNHB standard for the ^{192}Ir radiation beam

LNHB		Values (*Gy/C*)	uncertainty [(1)]	
Calibration of the standard			u_{iA}	u_{iB}
$N_K^{250\ kV}$	calibration coefficient in 250 kV x-ray beam	4.0933×10^7	---	0.0040
$N_K^{Cs\text{-}137}$	calibration coefficient in ^{137}Cs beam	4.1456×10^7	---	0.0065
$N_K^{Ir\text{-}192}$	interpolated calibration coefficient for ^{192}Ir beam	4.1209×10^7	---	0.0046
Measurement of current *I* and distance *d*				
I	ionization current / A	---	0.0015	0.0036
d	distance / mm			0.0003
Correction factors				
k_{att}	air and PMMA holder attenuation	1.0055	---	0.0019
k_{rn}	radial non uniformity correction	1.0057	---	0.0019
k_{st}	scatter correction	0.9972	---	0.0002
k_{dec}	decay correction	---	---	0.0001
Relative standard uncertainty				
	quadratic summation		0.0015	0.0064
	combined uncertainty of $\dot{K}_R$		0.0066	

[(1)] Expressed as one standard deviation

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

The main characteristics of the HDR ^{192}Ir source used at the LNE-LNHB are listed in Table 4.

Table 4. Characteristics of the LNE-LNHB ^{192}Ir source

After-loader unit	SagiNova
Manufacturer of source	Curium Netherlands B.V.
Source type	IR-192 HDR STRAHLER
Source Model Designation	IR2.A85-2
Source serial number	NLF 01 D90E-806
Estimated content activity of source	254 GBq (2024-05-02 12h UTC)
Capsule dimensions	0.9 mm diameter, 4.52 mm length
Capsule material	Stainless steel, AISI 316L
Source pellet dimensions	0.6 mm diameter, 3.5 mm length

4. Determination of the BIPM reference value

The BIPM does not possess an ^{192}Ir source. The reference value for the well-type HDR 1000 Plus ionization chamber is based on measurements made using the ^{192}Ir sources of the four laboratories participating in the BIPM.RI(I)-K8 comparison during the period 2009-2014. The stability of the well chamber is monitored using a sealed source of ^{137}Cs. The long-term reproducibility of the chamber established using this source is less than 1 part in 10^3 in relative value.

To derive a reference value for the well chamber, the BIPM determined its calibration coefficient at each NMI that participated in this on-going key comparison through calibration of the thimble-type NE 2571 ionization chamber. Using the NMI ^{192}Ir source, the calibration coefficient for the well-type chamber $N^{\mathrm{w}}_{K,\mathrm{BIPM}}$ was evaluated as

$$N^{\mathrm{w}}_{K,\mathrm{BIPM}} = \frac{\dot{K}_{\mathrm{R,\,BIPM}}}{I_w} \quad (6)$$

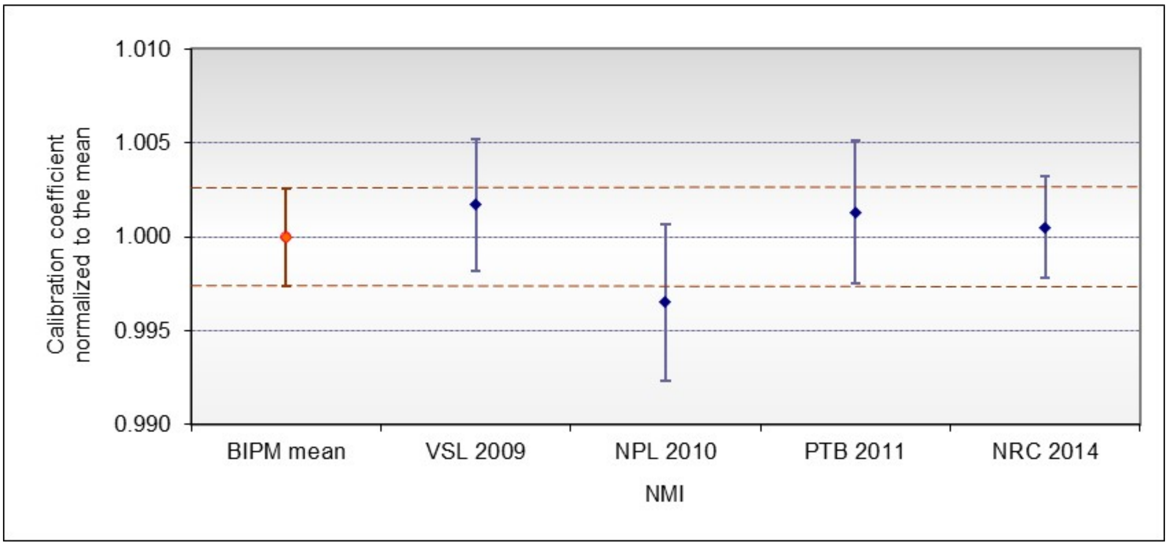
where $\dot{K}_{\mathrm{R,\,BIPM}}$ was the RAKR for the NMI source evaluated from the current determined by the NMI using the BIPM NE 2571 thimble chamber I^{th} and its calibration coefficient $N^{\mathrm{th}}_{K,\mathrm{BIPM}}$ determined by the BIPM ($\dot{K}_{\mathrm{R,\,BIPM}} = I^{\mathrm{th}} N^{\mathrm{th}}_{K,\mathrm{BIPM}}$), as described in the protocol for this on-going key comparison[a].

The well chamber current I_{w}, measured at the sweet-spot, was appropriately corrected to the reference conditions of measurements and normalized to the reference ambient conditions.

The mean of the well chamber calibration coefficients determined by the BIPM at each NMI that calibrated the NE 2571 chamber during the period 2009-2014 is taken as the reference value for the well chamber. To date, four NMIs (VSL, NPL, PTB and NRC) have participated in the BIPM.RI(I)-K8 comparison by calibrating the NE 2571 chamber (Alvarez *et al*. 2014a, Alvarez *et al*. 2014b, Kessler *et al*. 2015 and Kessler *et al*. 2014). The normalized calibration coefficients determined by the BIPM at these NMIs are shown in Figure 2. The standard deviation of the mean is 1.2 parts in 10^3; the evaluation of the standard uncertainty is explained in Section 7 and is represented in the graph by the dotted line.

[a] The value $N^{\mathrm{th}}_{K,\mathrm{BIPM}}$ for ^{192}Ir is calculated from the calibration coefficient determined at the BIPM in the ^{60}Co reference beam and a correction factor that accounts for the energy dependence of the chamber; this factor was calculated using a Monte Carlo code (Mainegra-Hing and Rogers 2006) to simulate the chamber response from 100 keV to ^{60}Co beams.

Figure 2. Normalized BIPM calibration coefficient for the well chamber



The uncertainty bars represent one standard uncertainty

5. Comparison measurements at the LNE-LNHB

The HDR 1000 Plus well chamber, together with its electrometer and probes for temperature, pressure and humidity, is used as a transfer system to determine a comparison result for those NMIs that do not provide calibrations of thimble-type ionization chambers. The ionization current of the well chamber was measured at the LNE-LNHB and the BIPM calibration coefficient was derived from these measurements and the LNE-LNHB determination of RAKR, as described in Section 3.

The essential details of the current measurements are reproduced here.

Sweet-spot

At the LNE-LNHB, measurements at seven dwell positions for the ^{192}Ir source with steps of 1 mm were done to determine the sweet-spot of the well chamber.

Charge and leakage measurements

At the sweet spot, three series of 20 charge measurements over 60 s each were made, the source being retracted to the afterloader and repositioned at the sweet-spot between each series. Measurements were also made at ±1 mm of the sweet-spot to confirm the position of the source. The standard deviation of the mean value of the three series was estimated to be 5 parts in 10^4.

Leakage current was measured before and after each series of measurements. The leakage correction, relative to the ionization current, was less than 1 part in 10^4.

Ambient conditions

The measurements are normalized to 293.15 K and 101.325 kPa. No humidity correction is applied.

Decay correction

The measurements are corrected for the decay of the source to the reference date of 2024-05-02, 12:00 UTC. The half-life for ^{192}Ir is 73.827 days with u_c = 0.013 days, taken from Bé *et al.* (1999).

6. Results of the comparison

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

The calibration coefficient $N^{\mathrm{w}}_{K,\text{LNE-LNHB}}$ for the LNE-LNHB is determined as

$$N^{\mathrm{w}}_{K,\text{LNE-LNHB}} = \frac{\dot{K}_{\text{R, LNE-LNHB}}}{I_{\mathrm{w}}} \tag{7}$$

where $\dot{K}_{\text{R,LNE-LNHB}}$ is the LNE-LNHB reference air kerma rate and I_{w} is the well chamber current, both corrected to the reference date 2024-04-03 12:00 UTC. The reference air kerma rate used for the present comparison was 36.73 mGy/h ± 0.66 % (k = 1).

As noted in Section 4, at the time of producing this report, four NMIs had participated in the BIPM.RI(I)-K8 comparison using the NE 2571 chamber (VSL, NPL, PTB and NRC). Taking the mean, $\bar{N}^{\mathrm{w}}_{K,\mathrm{BIPM}}$, of the four values determined by the BIPM at these NMIs, it is possible to evaluate the comparison result for the LNE-LNHB expressed as

$$R^{\mathrm{w}}_{K,\text{LNE-LNHB}} = \frac{N^{\mathrm{w}}_{K,\text{LNE-LNHB}}}{\bar{N}^{\mathrm{w}}_{K,\mathrm{BIPM}}} \tag{8}$$

For the LNE-LNHB, the comparison result R^{w}_{K} is 0.9990.

7. Uncertainties

As explained in Section 6, the BIPM calibration coefficient for the well chamber for ^{192}Ir beams is the mean of the calibration coefficients obtained at each NMI. Table 5 summarizes the uncertainty u_i corresponding to each calibration and the uncertainty of the mean value u, taking correlation into account.

Table 5. Relative standard uncertainty associated with the BIPM well chamber calibration at the NMIs

Relative standard uncertainty	u_i
$N^{\mathrm{w}}_{K,\mathrm{BIPM}}$ at the VSL (1st comparison 2009)	0.0035
$N^{\mathrm{w}}_{K,\mathrm{BIPM}}$ at the NPL (1st comparison 2010)	0.0042
$N^{\mathrm{w}}_{K,\mathrm{BIPM}}$ at the PTB (1st comparison 2011)	0.0038
$N^{\mathrm{w}}_{K,\mathrm{BIPM}}$ at the NRC	0.0027
$\bar{N}^{\mathrm{w}}_{K,\mathrm{BIPM}}$ [(a)] for ^{192}Ir	0.0026

[(a)] Correlation between the four determinations has been taken into account

The relative standard uncertainties associated with the well-type chamber calibration at the LNE-LNHB are listed in Table 6.

Table 6. Relative standard uncertainties associated with the well chamber calibration at the LNE-LNHB

Relative standard uncertainty	LNE-LNHB	
	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
^{192}Ir air kerma determination		
Reference air kerma rate $\dot{K}_\mathrm{R}$	0.0015	0.0064
Calibration of the well-type chamber		
Ionization current measured with well chamber, I_w	0.0002	0.0002
Positioning of source	0.0005	
Temperature, pressure correction	---	0.0001
Short-term stability	0.0005	---
$N^{\mathrm{w}}_{K,\mathrm{LNE\text{-}LNHB}}$	0.0017	0.0064

From Tables 5 and 6, the combined standard uncertainty u_c for the comparison result $R^{\mathrm{w}}_{K,\mathrm{LNE\text{-}LNHB}}$ is 7.1 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 also implemented some improvements to their standards, and the resulting changes adopted by the NMIs to update the comparison results are summarized in Table 7.

At the LNHB, the implementation of the ICRU 90 recommendations results in a decrease of the reference air kerma rate of 4.5 parts in 10^3, determined from the changes implemented in the 250 kV x-ray and ^{137}Cs radiation beams.

Table 7. 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
2022	NPL [b]			1.0045
2023	PTB [b]			1.0022
2024	LNHB [b]	0.9955	---	0.9990

[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 $D_i = (N_{K_R,\text{NMI}i} - N_{K_R,\text{BIPM}})/N_{K_R,\text{BIPM}} = R_{K,i} - 1$ (9)

and its expanded uncertainty $U_i = 2\, u_i$. (10)

The results for D_i and U_i, are expressed in mGy/Gy. Table 8 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 3.

Table 8. **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 (KCDB 2024)

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
b)	LNHB	-1.0	14.2

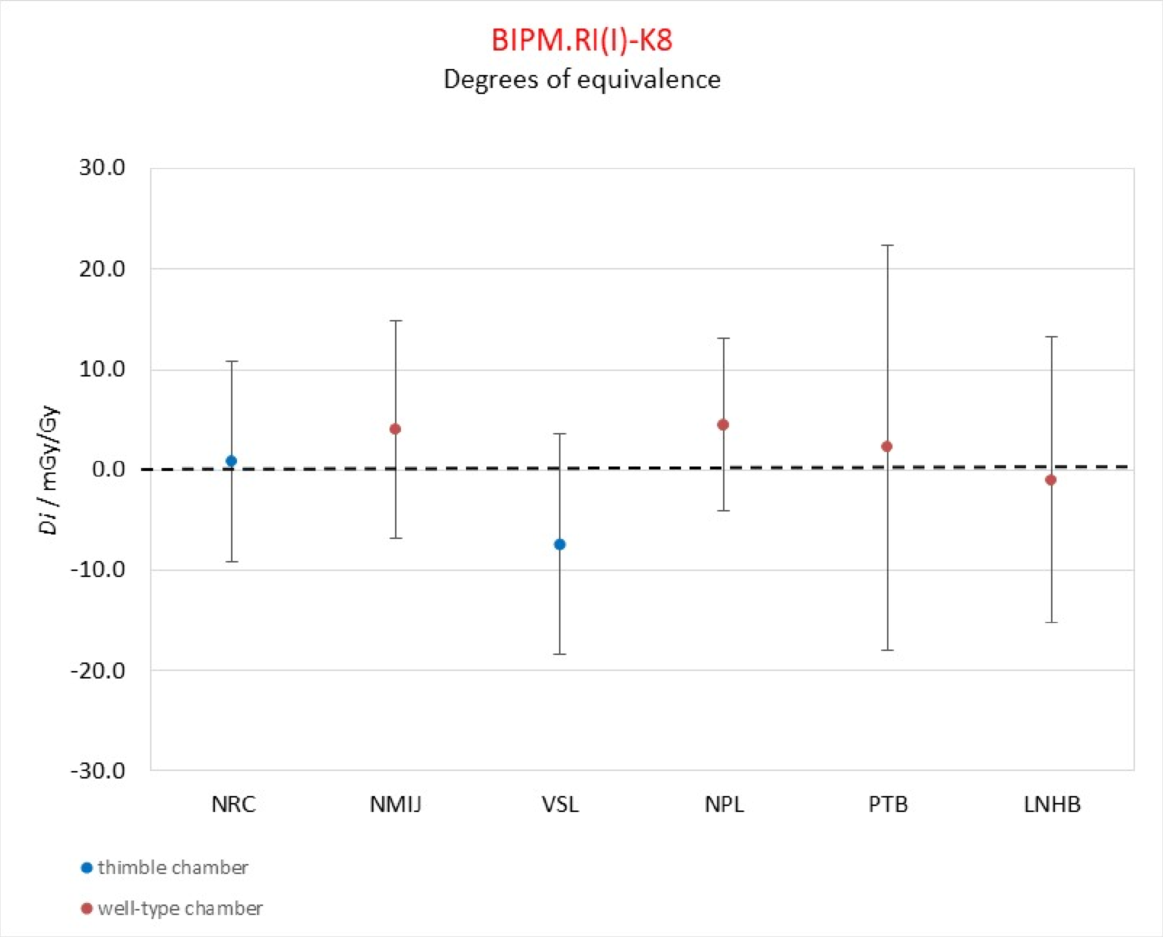
APMP.RI(I)-K8

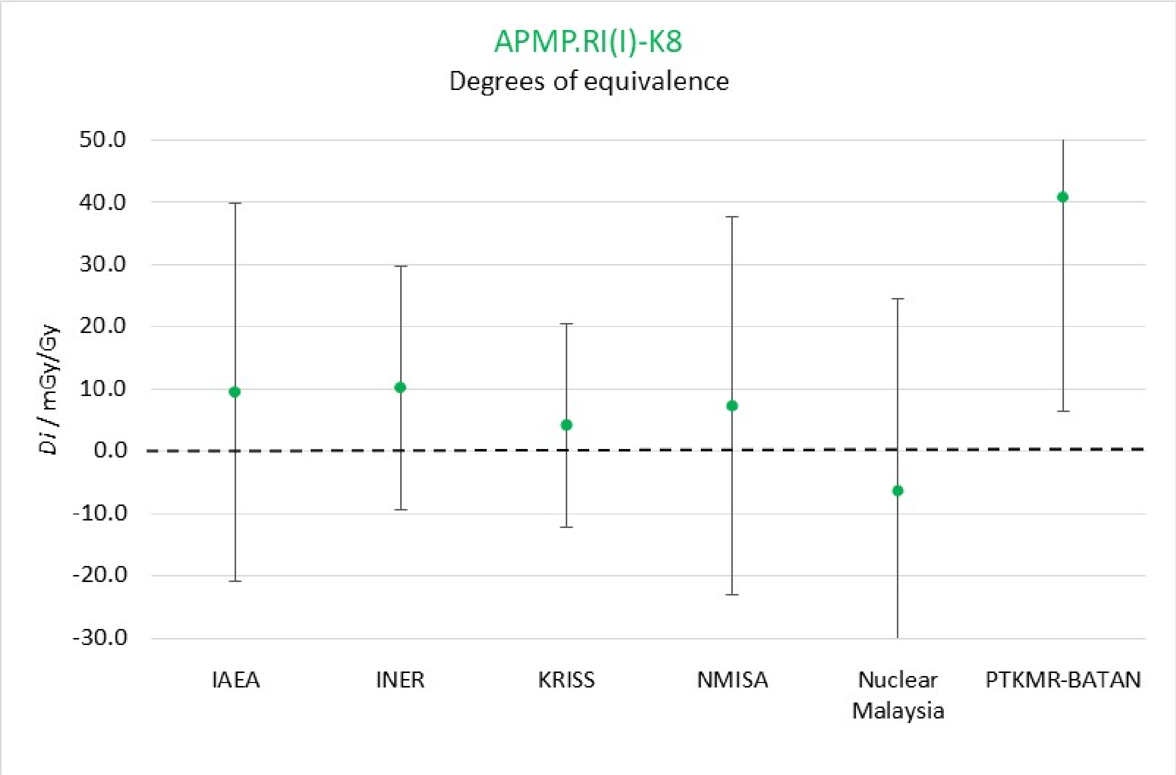
Lab i	D_i	U_i
	/ (mGy / Gy)	
IAEA	9.4	30.4
INER	10.1	19.6
KRISS	4.2	16.4
NMISA	7.3	30.4
Nuclear Malaysia	-6.4	30.8
PTKMR-BATAN	40.8	34.4

[a] results obtained using a thimble-type chamber

[b] results obtained using a well-type chamber

Figure 3. **Graph of degrees of equivalence with the KCRV**





10. Conclusion

The LNE-LNHB standard for the reference air kerma rate for ^{192}Ir gamma radiation compared with the BIPM reference value gives a comparison result of 0.9990 with a combined standard uncertainty u_c of 0.0071, in agreement, within the expanded uncertainty, with the other NMIs that have taken part in the BIPM.RI(I)-K8 comparison.

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