Key comparison BIPM.RI(I)-K8 of high dose-rate ^{192}Ir brachytherapy standards for reference air kerma rate of the NPL 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 National Physical Laboratory (NPL), United Kingdom, and of the Bureau International des Poids et Mesures (BIPM) was carried out at the NPL in June 2022. The comparison result, based on the calibration coefficients for a transfer standard and expressed as a ratio of the NPL and the BIPM standards for reference air kerma rate, is 1.0045 with a combined standard uncertainty of 0.0043.

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 data base (KCDB 2023) 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. The BIPM results are based on measurements using transfer standards, an NE 2571 thimble-type transfer ionization chamber and a well-type ionization chamber.

The National Physical Laboratory (NPL) took part in the comparison in June 2022 to update the previous comparison result of 2010 (Alvarez *et al.* 2014b) published in the KCDB. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories.

The previous comparison was done using the thimble chamber and the well-type chamber. Since 2011 the NPL provides traceability for HDR ^{192}Ir sources calibrating only well-type chambers. As a consequence, the present comparison was run using only the well-type chamber and the result is given in terms of the ratio of the calibration coefficient determined at the NPL 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 during the period 2009-2014 (VSL, NPL, PTB and NRC).

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 NPL reference value

The NPL primary standard is a spherical graphite cavity ionization chamber constructed at the NPL (Sander and Nutbrown 2006). The primary standard was originally commissioned for the measurement of Nucletron microSelectron-v1 ‘classic’ HDR ^{192}Ir brachytherapy sources. Since the publication of the NPL report in 2006, the primary standard was recommissioned for the HDR ^{192}Ir Flexisource in 2014, when the microSelectron-v1 source became obsolete and NPL replaced the microSelectron afterloader with a Flexitron afterloader. The recommissioning in 2014 and the implementation of the ICRU 90 recommendations at NPL in 2019 resulted in a refined set of some of the measured and Monte Carlo calculated conversion and correction factors for the HDR ^{192}Ir RAKR primary standard. The changes will be discussed in this section. The main characteristics of the standard are listed in Table 2.

Table 2. Characteristics of the NPL primary standard

Characteristic/Nominal values		TH100C
Dimensions	Inner diameter / mm	58.03
	Wall thickness / mm	3.8
Electrode	Length / mm	28.5
	Diameter / mm	3.1
Volume	Air cavity / cm^3	102.52
Graphite density	/ g cm^{-3}	1.75
Potential of HV electrode with respect to collecting electrode		-500

The RAKR is determined using the equation

$$\dot{K}_R = \frac{I_{\text{corr}} \cdot k_{\text{elec}}}{\rho_{\text{air}} \cdot V_{\text{air}}} \cdot \left(\frac{W_{\text{air}}}{e}\right) \cdot \frac{1}{(1-\overline{g})} \cdot \left(\frac{\overline{S}}{\rho}\right)_{\text{air}}^{\text{graph}} \cdot k_{\text{fl}}$$
$$\cdot \left(\frac{\overline{\mu}_{\text{en}}}{\rho}\right)_{\text{graph}}^{\text{air}} \cdot \prod_i k_i \cdot \left(\frac{d}{d_{\text{ref}}}\right)^2 \cdot \left(k_{\text{aasc}} \cdot k_{\text{catheter}} \cdot k_{\text{s}} \cdot k_{\text{dec}} \cdot k_h \cdot k_{Tp}\right) \qquad (1)$$

where

$\dot{K}_R$ is the RAKR at the chosen reference time t_{ref},

I_{corr} is the measured ionization current (i.e., measured charge per time) with leakage correction,

k_{elec} is the electrometer correction factor,

V_{air} is the volume of the air cavity,

ρ_{air} is the density of dry air at normal pressure and temperature,

W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in dry air,

$\overline{g}$ is the fraction of secondary electron energy lost to bremsstrahlung in air,

$(\overline{S}/\rho)_{\text{air}}^{\text{graph}} \cdot k_{\text{fl}}$ is the product of the ratio of the mean electron-fluence-weighted electron mass stopping power of graphite to that of air and the fluence perturbation correction factor (determined by Monte Carlo simulation),

$(\overline{\mu}_{\text{en}}/\rho)_{\text{graph}}^{\text{air}}$ is the ratio of the mean photon-energy-fluence-weighted photon mass energy-absorption coefficient of air to that of graphite (determined by Monte Carlo simulation),

$\prod_i k_i$ is the product of all remaining correction factors listed in Table 3, but not explicitly listed in equation (1), including polarity correction (determined by measurement), and wall correction (including stem scatter and central electrode correction), axial and radial non-uniformity correction (all determined by Monte Carlo simulation),

$(d/d_{\text{ref}})^2$ normalizes the current measured at the centre-to-centre source-to-chamber distance d = 1.433 m to the reference distance d_{ref} = 1 m,

k_{aasc} is the combined air attenuation and scatter correction factor which corrects for air attenuation and scatter between the source and the point of measurement,

k_{catheter} is the catheter attenuation correction factor which corrects for the attenuation of the photons emitted from the HDR ^{192}Ir source by the polyamide catheter inside the lead collimator,

k_{s} is the ion recombination correction factor,

k_{dec} is the decay correction factor which corrects the measured ionisation current at the time of measurement to the reference time t_{ref},

k_h is the humidity correction factor,

k_{Tp} is the temperature and pressure correction factor.

The values used for the physical constants, the correction factors entering in the determination of the RAKR and the associated uncertainties are given in Table 3.

Table 3. Physical constants and correction factors with their relative standard uncertainties of the NPL standard for the ^{192}Ir radiation beam

NPL		values	uncertainty [1]	
Physical Constants			100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
ρ_{air}	dry air density [2] / kg m^{-3}	1.2046	-	0.01
ρ_{graphite}	graphite density / kg m^{-3}	1750	-	0.04
$(\bar{\mu}_{\mathrm{en}}/\rho)^{\mathrm{air}}_{\mathrm{graph}}$	ratio of mass energy-absorption coefficients	1.0022	-	0.10
$(\bar{S}/\rho)^{\mathrm{graph}}_{\mathrm{air}} \cdot k_{\mathrm{fl}}$	product of mass stopping power ratio and fluence perturbation correction	1.0061	-	0.08 [3]
W_{air}/e	mean energy per charge / J C^{-1}	33.97	-	- [3]
$\bar{g}$	fraction of energy lost in radiative processes	1.0007	0.01	0.01
Correction factors				
k_{elec}	electrometer charge calibration	1.0000	-	0.11
k_{res}	electrometer resolution	0.0005	-	0.03
t	time / s	60	-	0.06
k_{Tp}	temperature and pressure correction	1.0000	-	0.05
R_{angular}	angular response		-	0.09
k_{aasc}	air attenuation and scatter correction	1.0165	0.02	-
k_{catheter}	catheter attenuation correction	1.0027	0.01	0.02
d_{pos}	catheter position in lead collimator / mm	0.25	-	0.03
d_{source}	source position within catheter along beam axis / mm	0.2	-	0.03
S_{lat}	lateral source positioning / mm	0.05	-	0.03
S_{spec}	source spectrum		-	0.10
$d_{\mathrm{cath\text{-}ap}}$	distance from catheter to rear surface of aperture / mm	299	-	0.01
$d_{\mathrm{ap\text{-}cham}}$	distance from front surface of aperture to chamber / mm	1020	-	0.01
k_{wall}	wall correction	1.0417	0.10	0.10
k_{an}	axial non-uniformity	0.9981	0.05	0.10
k_{rn}	radial non-uniformity	1.0000	0.01	0.02
k_{s}	ion recombination [4]	1.0028	-	0.02
k_{pol}	polarity	0.9995	0.02	-
k_{dec}	decay correction		-	0.01
k_{h}	humidity	0.997	-	0.05
Measurement of I / V				
V_{air}	chamber volume / cm^3	102.52	-	0.09
I	ionization current / A [5]		0.10	0.05
Relative standard uncertainty				
	quadratic summation		0.15	0.30
	combined uncertainty of $\dot{K}_{\mathrm{R}}$		0.34	

(1) Expressed as one standard deviation

$u_{i\mathrm{A}}$ represents the relative standard uncertainty estimated by statistical methods, type A

$u_{i\mathrm{B}}$ represents the relative standard uncertainty estimated by other means, type B

(2) Calculated density of dry air (0% relative humidity, 20 °C, 101.325 kPa, mole fraction of carbon dioxide in air assumed to be 400 µmol/mol) using equations published by Picard *et al*. 2008.

(3) Due to correlated uncertainties between the stopping power ratio and W_{air}/e, the uncertainty in W_{air}/e has been included in the combined uncertainty for the product $W_{\mathrm{air}}/e \cdot (\bar{S}/\rho)^{\mathrm{graph}}_{\mathrm{air}} \cdot k_{\mathrm{fl}}$.

(4) Ion recombination correction factor for a typical ionization current of 20 pA.

(5) Type A relative standard uncertainty for repeatability and type B relative standard uncertainty for leakage current. Ionization current measured as charge per time (see uncertainties for k_{elec}, k_{res} and t).

The corrections for the NPL standard and the essential details of the air kerma rate determination are briefly described in the following paragraphs.

Positioning

At the NPL, the primary standard cavity chamber TH100C is set up on a moveable carriage in front of a lead collimator which houses the radiation source as shown in Figure 1.

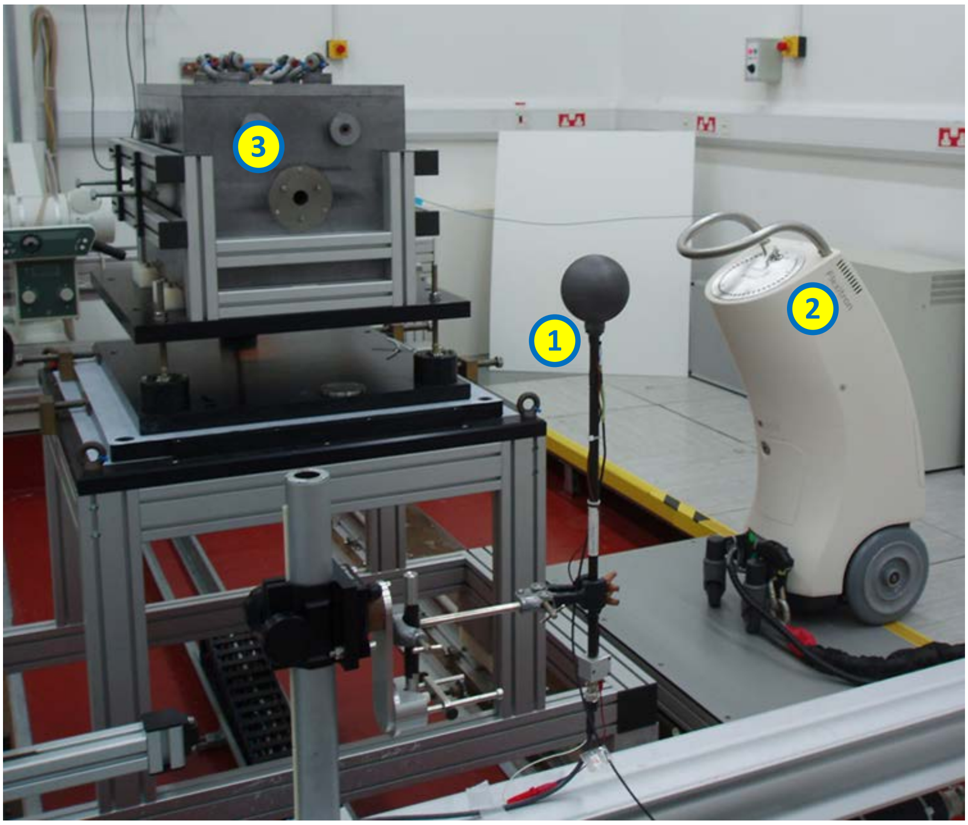


Figure 1. Set-up for HDR ^{192}Ir source calibrations in terms of RAKR at NPL.
❶ primary standard cavity chamber, ❷ HDR afterloader and ❸ lead collimator with front face aperture. The HDR ^{192}Ir source is inserted horizontally into the lead collimator through a polyamide catheter which is attached to the afterloader and clamped to the inside of the collimator side wall shown on the left-hand side of the picture.

The HDR ^{192}Ir brachytherapy source is inserted from the afterloader into the lead collimator through a polyamide plastic catheter with an inner diameter of 1.23 mm and an outer diameter of 1.68 mm. A conical aperture is inserted in the front face of the collimator such that the beam direction from the source centre to the reference point at the centre of the cavity chamber is at a right angle to the long axis of the source. The collimated beam is directed towards the primary standard cavity chamber, which is set up at a centre-to-centre source-to-chamber distance of 1433 mm. Both the source-to-chamber distance and aperture size were chosen to give a uniform field over the whole of the ionization chamber, which is circular in cross section. The measured ionization current is corrected to standard atmospheric conditions and normalised to 1 metre distance. Conversion and correction factors listed in equation (1) are applied to determine the reference air kerma rate for a reference time and date. The reference air kerma rate is derived from the mean of thirty separate measurements (multiple source transfers to the same dwell position). The conversion and correction factors applied to the measured ionization current are described in the following paragraphs.

Applied voltage and polarity

A collecting voltage of 500 V (positive polarity) is applied to the collecting and guard electrodes of the chamber at least 30 min before any measurements are made. The outer electrode (graphite sphere) is earthed, i.e., negative charge is usually collected. A correction factor of 0.9995 is applied to account for the polarity effect with a standard uncertainty of 2 parts in 10^4. The polarity correction factor was initially based on the mean of four pairs of measurements with positive and negative polarizing voltage applied. At the recommissioning for the Flexisource, the polarity correction factor was remeasured and based on sixteen pairs of measurements to improve the statistics.

Ion recombination (k_s)

The ion recombination correction factor was determined from measurements made at the NPL in 50 kV X-ray beams with different X-ray tube currents, using the Niatel/Boutillon method (Boutillon 1998). The recombination correction factor k_s can be expressed as

$$k_{\mathrm{s}} = 1 + k_{\mathrm{init}} + k_{\mathrm{vol}} I_V \qquad (2)$$

where k_{init} is the initial recombination, k_{vol} is the volume recombination coefficient and I_V is the current measured for the applied voltage V.

Using equation (2) the correction factor k_s for losses due to ion recombination for the ^{192}Ir source, applied to the measured current to determine the reference air kerma rate, was found to be 1.0028 with a standard uncertainty of 2 parts in 10^4.

Charge and leakage measurements

The charge Q, collected by the primary standard is measured using a Scanditronix Wellhöfer Dose 1 electrometer. The measured ionization current was corrected for the leakage current. This correction was in relative value less than 5 parts in 10^4.

Ambient conditions

The measurements are normalized to 293.15 K and 101.325 kPa. Relative humidity was around 50 %.

Attenuation and scattering in the chamber wall (k_{wall})

When the ICRU 90 recommendations were implemented for NPL's HDR ^{192}Ir primary standard, three Monte Carlo calculated conversion and correction factors, previously based on ICRU Report 37 (ICRU 1984), were re-evaluated: 1) the ratio of mass energy-absorption coefficients (air-to-graphite), 2) the product of the mass stopping power ratio (graphite-to-air) and the fluence perturbation correction factor, and 3) the wall correction factor for photon attenuation and scattering in the graphite wall of the standard. k_{wall} was recalculated based on a refined chamber geometry, and now includes the previously separately listed central electrode correction factor and measured stem scatter correction factor. The actual chamber was modelled with real materials, including the central electrode and the top part of the chamber stem which is exposed to the primary photon beam from the ^{192}Ir source. k_{wall} was calculated as the ratio of the dose to the air cavity of the actual chamber (assuming no photon attenuation and scatter), divided by the dose to the air cavity with the incident photons being attenuated and scattered. Monte Carlo techniques were used to model the gamma spectrum from a shielded Elekta HDR

^{192}Ir Flexisource and associated lead collimator, and the cavity chamber. The ^{192}Ir source spectrum (Bé *et al*. 1999) used for the simulations included all photons which contribute at least 0.1% to the ^{192}Ir spectrum. The value for k_{wall} is 1.0417 with a standard uncertainty of 1.4 parts in 10^3 which includes the type A uncertainty of all three Monte Carlo calculated factors mentioned in this section. The conversion and correction factors are listed in Table 3.

Air attenuation and scattering between the source and the chamber (k_{aasc})

The correction factor for air attenuation and scattering between the source and the chamber was remeasured using a multiple-distance method during the recommissioning of the standard for the Flexisource. The value of k_{aasc} is 1.0165 at standard temperature and pressure with a standard uncertainty of 2 parts in 10^4.

Radial and axial non-uniformity correction (k_{rn}, k_{an})

The correction for radial non-uniformity, k_{rn}, is required to account for the change in the ^{192}Ir spectrum over the chamber volume perpendicular to the beam axis and is estimated to be unity with a standard uncertainty of 2 parts in 10^4. The correction for axial non-uniformity, k_{an}, is required to account for the change in the ^{192}Ir spectrum over the chamber volume in the direction of the beam axis and is estimated to be 0.9981 with a standard uncertainty of 1 part in 10^3. This estimation is based on calculations using Monte Carlo techniques.

Catheter attenuation correction (k_{catheter})

The catheter attenuation correction factor corrects for the attenuation of the photons emitted from the HDR ^{192}Ir source by the polyamide catheter inside the lead collimator. Up to 2019, the effect of the catheter attenuation was assumed to be negligible, and a correction factor of unity was assigned. However, an additional standard uncertainty of 5 parts in 10^4 was included in the overall uncertainty for k_{aasc}, based on Monte Carlo simulations. In 2019, the catheter attenuation correction factor was measured by adding thin sheets of polyamide with different thicknesses in the ^{192}Ir beamline. The measured correction factor, k_{catheter}, was found to be 1.0027 with a standard uncertainty of 2 parts in 10^4.

Changes in the primary standard correction factors since NPL's previous K8 key comparison

The first revision of correction factors after the 2010 BIPM.RI(I)-K8 NPL key comparison (Alvarez *et al.* 2014b) was carried out in 2014, when the type of HDR ^{192}Ir radiation source used at NPL was changed from the Nucletron microSelectron-v1 'classic' source to the Elekta Flexisource. All previous Monte Carlo calculated correction factors were adopted at this stage. However, the separately reported central electrode correction factor of 0.9984 was removed from the list (resulting in a change of +0.16 %) because it was already included in the wall correction factor. The correction factors for stem scatter, polarity correction, and air attenuation and scatter were re-evaluated by measurement, leading to a change of +0.10 %, so the overall correction factor for NPL's HDR ^{192}Ir primary standard changed by +0.26 % in 2014.

In 2019, a further revision of conversion and correction factors was implemented. The change in the overall correction factor for NPL's HDR ^{192}Ir primary standard due to the measured catheter attenuation correction (+0.27 %) was almost completely compensated by the –0.23 % overall change in the three re-evaluated Monte Carlo calculated conversion and correction factors (see description of k_{wall}) because of both the inclusion of the stem scatter correction factor in k_{wall} and the implementation of the ICRU 90 recommendations. A small adjustment of +0.01 % was also made to the air density, ρ_{air} (see equation (1)). The air density appears in the denominator, so this results in a change of -0.01% in the primary standard chamber factor.

The overall change in the primary standard chamber factor from the 2010 BIPM.RI(I)-K8 NPL key comparison to the 2022 BIPM.RI(I)-K8 NPL key comparison was found to be +0.29 %.

The main characteristics of the Elekta HDR ^{192}Ir Flexisource used at NPL are listed in Table 4.

Table 4. Characteristics of the NPL ^{192}Ir source

After-loader unit	Elekta Flexitron HDR
Manufacturer of source	Curium Netherlands B.V.
Source model designation	136.147
Source serial number	D85E8185
Estimated content activity of source	391.7 GBq at 2022-03-10, 08:30 UTC
Capsule dimensions	0.86 mm diameter, 4.6 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 1×10^{-3} in relative value.

To derive a reference value for the well chamber, the BIPM determines its calibration coefficient at each NMI that participates 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 $N_{K,\mathrm{BIPM}}^{\mathrm{w}}$ is evaluated as

$$N_{K,\mathrm{BIPM}}^{\mathrm{w}} = \frac{\dot{K}_{\mathrm{R,\,BIPM}}}{I_w} \tag{3}$$

where $\dot{K}_{\mathrm{R,\,BIPM}}$ is 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 $N_{K,\mathrm{BIPM}}^{\mathrm{th}}$ determined by the BIPM ($\dot{K}_{\mathrm{R,\,BIPM}} = I^{\mathrm{th}} N_{K,\mathrm{BIPM}}^{\mathrm{th}}$), as described in the protocol for this on-going key comparison[a].

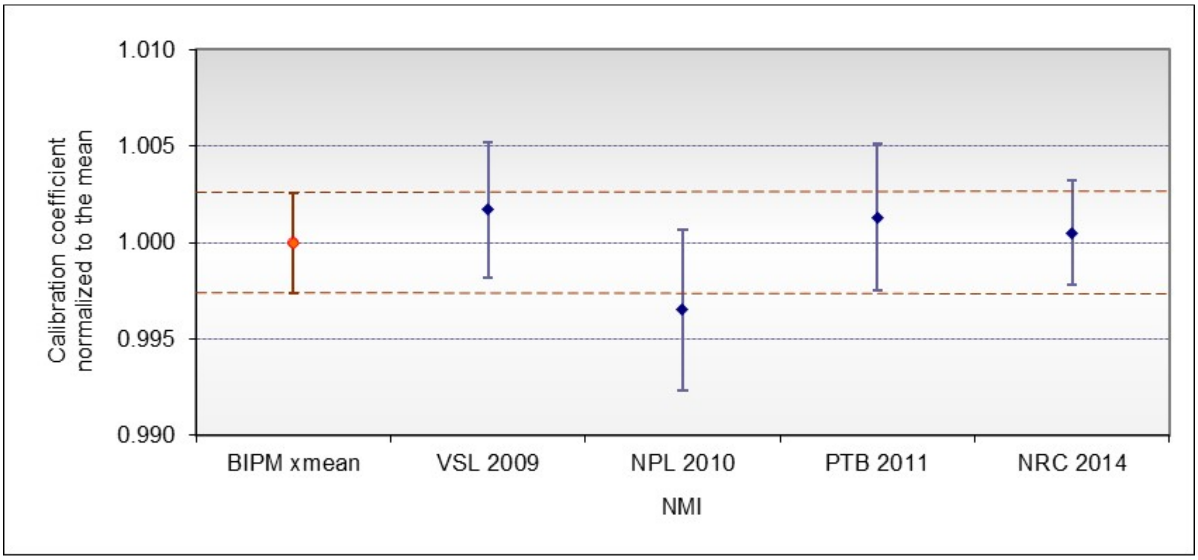
The well chamber current I_w, measure at the sweet-spot, is appropriately corrected to the reference conditions of measurements and normalized to the reference ambient conditions.

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

[a] The value $N_{K,\mathrm{BIPM}}^{\mathrm{th}}$ 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 and Rogers 2006) to simulate the chamber response from 100 keV to ^{60}Co beams.

deviation of the mean is 1.2×10^{-3}; the evaluation of the standard uncertainty is explained in Section 7 and is represented in the graph by the dotted line.

Figure 2. Normalized BIPM calibration coefficient for the well chamber



The uncertainty bars represent one standard uncertainty

5. Comparison measurements at the NPL

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 NPL and the BIPM calibration coefficient was derived from these measurements and the NPL determination of RAKR, as described in Section 3.

The essential details of the current measurements are reproduced here.

Sweet-spot

At the NPL, measurements at a series of dwell positions for the ^{192}Ir source showed the sweet-spot of the well chamber to be at 49.5 mm, measured from the inside surface of the base plate of the well chamber insert.

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 corrected for leakage, which was measured before and after each series. This correction was, in relative value, less than 1×10^{-3}.

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 2022-04-01, 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 $N^{w}_{K,\mathrm{NPL}}$ for the NPL is determined as

$$N^{w}_{K,\mathrm{NPL}} = \frac{\dot{K}_{\mathrm{R,\,NPL}}}{I_w} \tag{4}$$

where $\dot{K}_{\mathrm{R,NPL}}$ is the NPL reference air kerma rate and I_w is the well chamber current.

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, $\overline{N}^{\mathrm{w}}_{K,\mathrm{BIPM}}$, of the four values determined by the BIPM at these NMIs, it is possible to evaluate the comparison result for the NPL expressed as

$$R^{\mathrm{w}}_{K,\mathrm{NPL}} = \frac{N^{w}_{K,\mathrm{NPL}}}{\bar{N}^{w}_{K,\mathrm{BIPM}}} \tag{5}$$

For the NPL, the comparison result R^{w}_{K} is 1.0045.

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 summarises 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	0.0038
$N^{\mathrm{w}}_{K,\mathrm{BIPM}}$ at the NRC	0.0027
$\overline{N}^{\mathrm{w}}_{K,\mathrm{BIPM}}$ [(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 NPL are listed in Table 6.

Table 6. Relative standard uncertainties associated with the well chamber calibration at the NPL

Relative standard uncertainty	NPL	
	u_{iA}	u_{iB}
^{192}Ir air kerma determination		
Reference air kerma rate $\dot{K}_R$	0.0015	0.0030
Calibration of the well-type chamber		
Ionization current measured with well chamber, I_w	0.0002	0.0002
Temperature, pressure correction	---	0.0001
Short-term stability	0.0005	---
$N^{w}_{K,\mathrm{NPL}}$	0.0016	0.0030

From Tables 5 and 6, the combined standard uncertainty u_c for the comparison result $R^{w}_{K,\mathrm{NPL}}$ is 4.3×10^{-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 summarised in Table 7.

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]	0.9966	1.0003	1.0057
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

[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 $D_i = (N_{K_R,\mathrm{NMI}i} - N_{K_R,\mathrm{BIPM}})/N_{K_R,\mathrm{BIPM}} = R_{K,i} - 1$ (6)

and its expanded uncertainty $U_i = 2\ u_i$. (7)

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 2023)

BIPM.RI(I)-K8

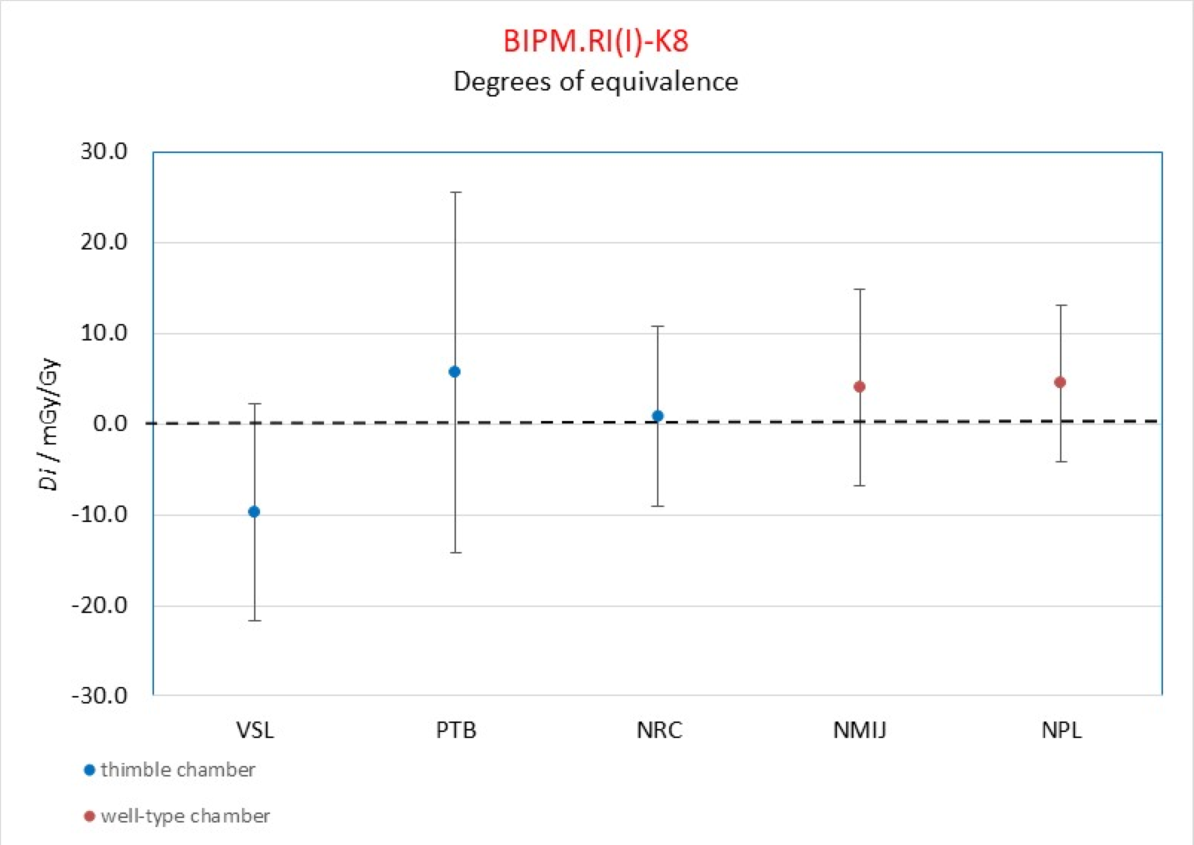
	Lab i	D_i / (mGy / Gy)	U_i / (mGy / Gy)
a)	VSL	-9.7	12.0
a)	PTB	5.7	19.8
a)	NRC	0.9	10.0
b)	NMIJ	4.0	10.8
b)	NPL	4.5	8.6

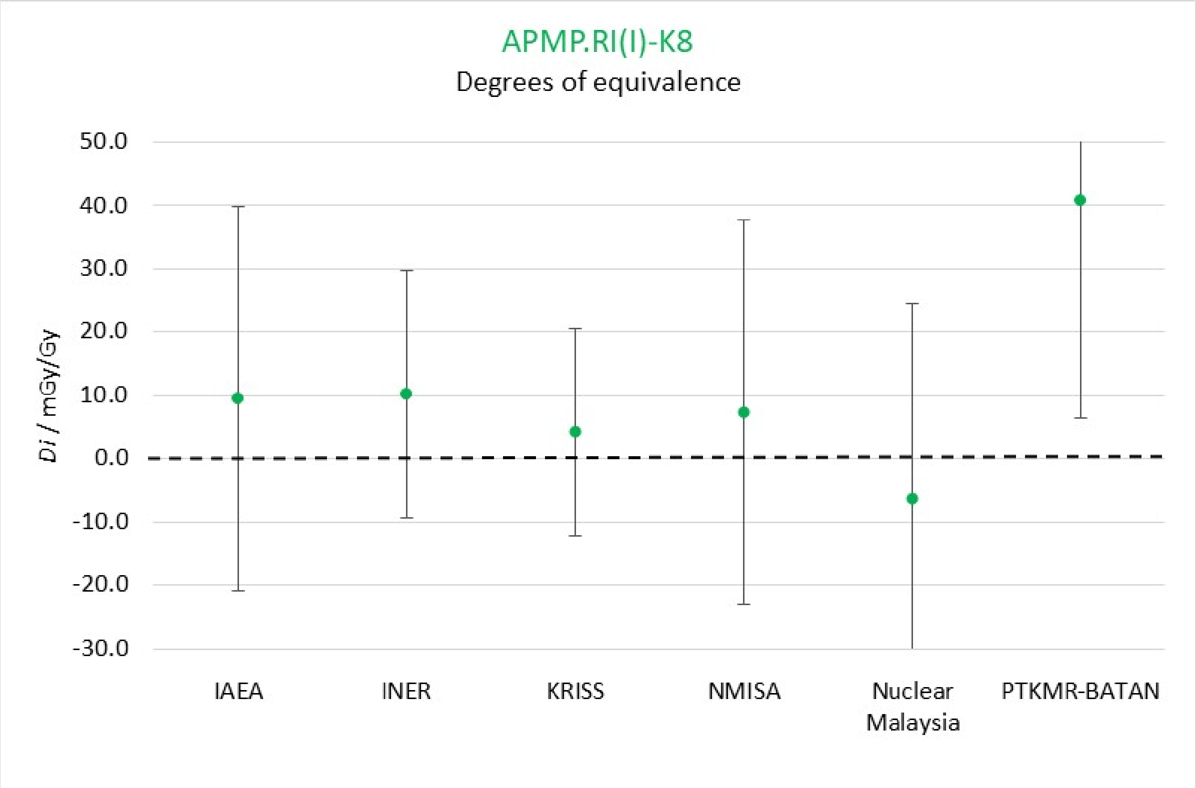
[a] results obtained using a thimble-type chamber
[b] results obtained using a well-type chamber

APMP.RI(I)-K8

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

Figure 3. Graph of degrees of equivalence with the KCRV





9. Conclusion

The NPL standard for the reference air kerma rate for ^{192}Ir gamma radiation compared with the BIPM reference value gives a comparison result of 1.0045 with a combined standard uncertainty u_c of 0.0043.

The degrees of equivalence with the PTB, NRC, NMIJ and the VSL, so far the only four other participants in the BIPM.RI(I)-K8 comparison, are within the expanded uncertainty.

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