

Comparison protocol for the measurement of Reference Air Kerma Rate for HDR ^{192}Ir , BIPM.RI(I)-K8

1. Introduction

The CCRI(I) Brachytherapy Standards Working Group (BSWG(I)) proposed at their meeting of November 2005 to start a comparison of reference air kerma rate (RAKR or \dot{K}_R) for ^{192}Ir determined using the NMI primary standards or methods based on their primary instruments.

The principal concern of the BSWG(I) is that high dose rate (HDR) brachytherapy ^{192}Ir medical sources have a relatively high uncertainty in use. There are several causes for this high uncertainty: calibrations not directly traceable to absorbed dose to water, complicated dose planning, accurate localization of the sources in the patient according to the treatment plan, etc.

Although the development of absorbed dose to water standards for ^{192}Ir is underway, these are unlikely to be realized for some time. It was felt that an increase in confidence in the \dot{K}_R standards themselves could be achieved by determining their degree of equivalence through an international comparison of \dot{K}_R standards for ^{192}Ir .

This comparison has as its objective to establish the degrees of equivalence between national standards or methods for determining \dot{K}_R . For this purpose, it is proposed to use a thimble-type chamber as the transfer instrument. In addition, for those National Metrology Institutes (NMIs) that do not provide calibrations for thimble chambers, degrees of equivalence can be established using a well-type chamber.

This protocol has been revised and approved by the BSWG(I).

2. Reference air kerma rate

The dosimetric quantity for the comparison is the reference air kerma rate (RAKR), which is defined in ICRU Report 58 (ICRU 1997) as:

$$\dot{K}_R = \dot{K}(d) \cdot \left(\frac{d}{d_{\text{ref}}} \right)^2 \quad (1)$$

where $\dot{K}(d)$ is the air kerma rate measured at distance d . The \dot{K}_R is evaluated at the reference distance $d_{\text{ref}} = 1 \text{ m}$ *in vacuo*. Its recommended units are Gy s^{-1} or $\mu\text{Gy h}^{-1}$.

3. Comparison methodology

3.1 Participants

As no facility is available at the BIPM, the measurements will take place at the NMIs. The BIPM will take two transfer instruments to each NMI for their calibration in terms of \dot{K}_R .

The institutes proposed as participants are indicated in Table 1:

Table 1. List of NMIs proposed as participants in the comparison.

Laboratory		Contact person / e-mail	Country
LNMRI-IRD	Laboratório Nacional de Metrologia das Radiações Ionizantes	Carlos da Silva Carlos@ird.gov.br	Brazil
LNE-LNHB	LNE-Laboratoire National Henri Becquerel	Isabelle Aubineau Laniece isabelle.aubineau-laniece@cea.fr	France
PTB	Physikalisch-Technische Bundesanstalt	Ulrike.Ankerhold Ulrike.Ankerhold@ptb.de	Germany
BARC	Bhabha Atomic Research Centre	A.K. Mahant amahant@barc.gov.in	India
ENEA-INMRI	ENEA Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti	Marco D'Arienzo marco.dariento@enea.it	Italy
NMIJ/AIST	National Metrology Institute of Japan	Tadahiro Kurosawa tadahiro-kurosawa@aist.go.jp	Japan
KRISS	Korea Research Institute of Standards and Science	Kook Jin Chun chunkj@kriss.re.kr	Korea
VSL	VSL Dutch Metrology Institute	Jacco de Pooter JdPooter@vsl.nl	Netherlands
VNIIM	D.I. Mendeleev All-Russian Institute for Metrology	Igor Kharitonov khia@vniim.ru	Russian Federation
NPL	National Physical Laboratory	Thorsten Sander Thorsten.Sander@npl.co.uk	United Kingdom
NIST	National Institute of Standards and Technology	Michael G. Mitch michael.mitch@nist.gov	USA
NRC-MSS	National Research Council Canada	McEwen, Malcolm Malcolm.McEwen@nrc-cnrc.gc.ca	Canada

3.2 Comparison conditions

The concept of this comparison is to let the NMIs make the calibration at the distance for which they normally provide thimble-chamber calibrations, using their usual set-up. Under these conditions they should already have the correction factors necessary, together with their uncertainties.

Reference environmental conditions

The temperature, pressure and humidity at the time of the measurements should be reported; the measurements must be normalized to the reference environmental conditions of 20 °C and 101.325 kPa. The reference relative humidity is 50 %.

Time

When reporting the results, the Coordinated Universal Time UTC of the measurements should be clearly indicated.

Positioning

The calibration distance and use of special accessories (jig positioning, type of catheter, collimation, etc) must be specified. This might give rise to additional components to be included in the uncertainty budget.

¹⁹²Ir source

Each participant may choose their usual source construction/type and appropriate activity. However, as the transfer chamber responses are dependent on the ¹⁹²Ir source design, the source reference code, manufacturer and apparent activity should be reported with the thimble-chamber calibration coefficients, see Annex A: Reporting form for results of the comparison for Reference Air Kerma Rate for HDR ¹⁹²Ir. This will enable subsequent analysis if discrepancies become apparent.

3.3 Instruments for the comparison

The instruments proposed for use in this comparison are:

- Thimble transfer chamber NE 2571 serial number 2806, see characteristics in Table 2,
- Well chamber Standard Imaging HDR 1000 Plus, part number 90008, serial number A061525, see specifications in Table 3.

The thimble chamber will travel without an electrometer; each NMI will calibrate the chamber with its own equipment, as it does for their customers: charge or current measurement system, temperature and pressure probes, high voltage power supply. The BIPM personnel will normally operate the well-chamber system. The NMI is requested to provide the catheter needed for the source insertion and to assist with the measurements to optimize the source location (that is, locate the ‘sweet-spot’).

Before and after each comparison, the thimble chamber will be calibrated at the BIPM in the reference ⁶⁰Co γ -ray and CCRI 250 kV x-ray fields to evaluate its stability and the uncertainty component u_{stab} .

The stability of the well chamber is determined by current measurements before and after each comparison using ^{166m}Ho and ¹³⁷Cs reference sources at the BIPM.

3.3.1 Thimble chamber

The thimble chamber should be calibrated with the build-up cap provided, with its reference mark (height) centred on the source mid-plane, with the line on the stem facing the source and with the principal axis of the chamber parallel to the axis of the source. If this positioning is not possible at the NMI, the position actually used must be reported. Additional recommendations are the following:

- The chamber should be left in the measurement laboratory for an appropriate period to allow thermal equilibrium of the chamber to be reached.
- Pre-irradiation with around 2 Gy is considered to be appropriate.

Note that, depending on the electrometer used, the desired collecting potential can be achieved either by applying a negative potential to the HV electrode (the collector remaining at virtual ground) or by applying a positive potential to the collector (the HV electrode remaining at ground). In determining the mode of operation of a particular measuring system, the sign of the collected charge should not be used as this is sometimes inverted within the electrometer. The electrometer manual provided by the manufacturer might provide the required information.

Table 2. Characteristics of thimble chamber NE2571

Characteristics	Nominal Value	
Dimensions	Inner diameter	6.3 mm
	Wall thickness	0.065 g cm ⁻²
	Cavity length	24.0 mm
	Tip to reference point	13 mm
Electrode	Diameter	1.0 mm
	Length	21.0 mm
Volume	Air cavity	0.6 cm ³
Wall	Material	Graphite
	Density	1.7 g cm ⁻³
Build-up cap	Material	Delrin
	Thickness	0.551 g cm ⁻²
Potential of HV electrode with respect to collecting electrode		-250 V

3.3.2 Well chamber HDR 1000 Plus, part number 90008

The well-chamber system consists of:

- Electrometer Standard Imaging model MAX 4000 serial E060762,
- Well chamber Standard Imaging model HDR 1000 Plus 90008 serial A061525,
- Holder HDR 1000 – part number 70010, insert for the ¹⁹²Ir source,
- Monitor for ambient conditions Almemo 2590-3S H09070630,
- Probe temperature 1 Almemo FNA 6119070060,
- Probe temperature 2 and humidity Almemo FHA646 6 9080089,
- Probe pressure Almemo FDA612-SA 9080543,
- Laptop and communication accessories.

Care should be taken that the reference point of the insert – the black dot – always coincides with the reference point indicated by a dot on the top of the well chamber, and that the

catheter is pushed to the bottom of the insert and securely fixed with the screw on top of the holder.

The well-chamber response depends on the source position inside the chamber and the stated calibration coefficient applies only if the source is inserted to the point of maximum chamber response (sweet spot). The well chamber has its nominal maximum response at about 50 mm from the bottom of the chamber insert. Each NMI should assist in the determination of this position of maximum chamber response (by stepping the brachytherapy source through the well chamber) and the position of this point shall be reported in the comparison report as the distance (in mm) from the centre of the ^{192}Ir source to the tip of the plastic catheter.

To estimate the sensitivity to source positioning, it is recommended to make three sets of measurements, one for the sweet spot and two for the sweet spot plus or minus 0.5 mm. Each set should have three series of ten measurements, each measurement with an integration time of 60 seconds.

It is advisable to place the well chamber on a low-scatter support at a distance of 1 metre or more (and not less than 60 cm) from any wall and from the floor of the calibration room (Chang *et al* 2008).

Table 3. Characteristics of well chamber HDR 1000 90008 and insert 70010

Characteristics		Nominal Value
Dimensions	Height	15.6 cm
	Well chamber	Diameter
Insert 70010	Diameter	3.5 cm
	Height	12.1 cm
Volume		245 cm ³
Potential of HV electrode with respect to collecting electrode		-300 V
Nominal source reference points		Black dot on the insert and dot on the top of the chamber
		50 mm from bottom of chamber insert (<i>sweet-spot</i>)

3.4 Calibration coefficients

3.4.1 Thimble chamber

Each participant is requested to determine the calibration coefficient N_K^{th} for the thimble chamber and to provide:

- all the correction factors applied
- the value of the reference air kerma rate at a given reference date
- the reference date and the half life used
- the raw current measured using the thimble chamber
- the environmental conditions

- the detailed uncertainty budget, as determined using their reference standard/method

The calibration coefficient would normally be determined in accordance with equation (2), with the thimble chamber positioned at the usual NMI calibration distance d :

$$N_K^{\text{th}} = \frac{\dot{K}_R}{(M_{\text{raw}} - M_{\text{leak}}) \cdot k_{\text{ele}} \cdot k_d \cdot k_{\text{dec}} \cdot k_{PT} \cdot \prod_i k_i} \quad (2)$$

where

\dot{K}_R is the RAKR determined with the reference standard/method at d_{ref} ,

M_{raw} is the raw current measurement without any correction,

M_{leak} is the leakage or background current measurement,

k_{ele} is the calibration coefficient for the electrometer used in the measurement process,

k_d is the distance correction to d_{ref} ,

k_{dec} is the correction factor for radioactive decay of the source,

k_{PT} is the correction factor for atmospheric conditions, and

k_i represents any other appropriate correction factors such as non-uniformity of the photon fluence, anisotropy, short-term stability, etc.

3.4.2 Well chamber

Each participant is requested to provide

- the value of the reference air kerma rate at a given reference date
- the reference date and the half life used
- the detailed uncertainty budget, as determined using their reference standard/method

The participant provides an appropriate catheter for its source and assists in identifying the chamber sweet-spot position. Once this position has been identified and verified as indicated in section 3.3.2., the BIPM personnel will make the measurements using their equipment and the BIPM data acquisition programme. The ionization current measured by the electrometer is normalized to the reference temperature and pressure, corrected for decay to the reference date, and corrected for ion recombination depending on the ionization current actually measured. The BIPM determines the calibration coefficient $N_{K,\text{NMI}}^{\text{w}}$ for the well-type chamber as

$$N_{K,\text{NMI}}^{\text{w}} = \frac{\dot{K}_{R,\text{NMI}}}{(M_{\text{raw}} - M_{\text{leak}}) \cdot k_{\text{ele}} \cdot k_{\text{ion}} \cdot k_{\text{dec}} \cdot k_{PT}} \quad (3)$$

where:

$\dot{K}_{R,\text{NMI}}$ is the RAKR determined by the NMI with the reference standard/method,

M_{raw} is the raw current measured by the BIPM without any correction,

M_{leak} is the leakage or background current measurement,

k_{ele} is the calibration coefficient for the BIPM electrometer used in the measurement process,

k_{ion} is the correction factor for ion recombination in the well chamber,

k_{dec} is the correction factor for radioactive decay of the source, and

k_{PT} is the correction factor for atmospheric conditions.

If the NMI provides the calibration of the thimble chamber, then the BIPM also determines the calibration coefficient $N_{K_R, \text{BIPM}}$ for the well type chamber as expressed in (3) but in this case the RAKR is evaluated from the current measured with the thimble chamber and the N_K determination for this chamber at the BIPM. This is essentially a BIPM determination of the RAKR for the NMI source. The aim of calculating $N_{K, \text{BIPM}}^{\text{w}}$, which is clearly correlated with $N_{K, \text{NMI}}^{\text{th}}$, is to evaluate a reference value for the well chamber (determined as a mean of values obtained at several NMIs) that can subsequently be used to determine a comparison result and its corresponding degree of equivalence for those NMIs that don't provide a calibration of the thimble chamber and use only the well chamber.

3.5 Schedule for the comparison

The comparison normally takes three days during which the NMI calibrates the thimble chamber and the BIPM makes measurements using the well chamber. It is expected that the NMI will submit their results within 4 weeks and a Draft A report will be produced by the end of the following month. As the comparison is ongoing, a participant may join at any time and schedule measurements for a period agreed between the NMI and the BIPM.

3.6 Transport arrangements and costs

According to the “BIPM Measurement and Consultancy Services Policy” (BIPM/DIR-P-01), the comparisons of national measurement standards of Member States are carried out without charge. Normally, the BIPM personnel travel with the two transfer instruments to the NMI and the electrometer and accessories are sent in advance, according to the schedule agreed. The BIPM will arrange the ATA carnets and instructions for non-European Member States and all transport. For bilateral comparisons carried out in the laboratories of an NMI, the BIPM will pay the travel costs of its staff members, the subsistence indemnity and the costs of transport of the BIPM equipment to the NMI. It is requested that the NMI pays the local hotel accommodation for the BIPM staff members and the costs of transport of the BIPM equipment back to the BIPM including those costs incurred by the BIPM if it has to make some arrangements for the shipment and customs clearance operations.

4. Analysis of the results

There are effectively two comparisons held in parallel based on the two different types of transfer chamber. Nevertheless, only the results of the thimble chamber will be used to evaluate the degrees of equivalence; it provides a more direct way to compare the NMI determination of the RAKR based on different primary standards and methods. The results using the well type chamber will provide information about the dissemination of the calibration of this chamber type to the hospitals. In case that the NMI does not have the

facility to calibrate the thimble chamber, the degrees of equivalence for this NMI will be evaluated using the well-type ionization chamber measurements.

4.1 Thimble chamber comparison result

The result of the thimble chamber comparison, R_K^{th} , is expressed in the form

$$R_K^{\text{th}} = \frac{N_{K,\text{NMI}}^{\text{th}}}{N_{K,\text{BIPM}}^{\text{th}}} \quad (4)$$

The value $N_{K,\text{BIPM}}^{\text{th}}$ 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 *et al* 2006) to simulate the chamber response from 100 keV to ^{60}Co beams.

The calibration coefficient in ^{60}Co is taken as the mean value of the calibration coefficients made at the BIPM prior to those made at the NMI (pre-NMI) and those made afterwards (post-NMI); from these measurements, the combined standard uncertainty u_{BIPM} is calculated.

To maintain confidentiality for this ongoing comparison, the individual calibration coefficients for the thimble chamber will not be disclosed and only the result for R_K^{th} will be published in the comparison report.

As well as providing information on the different primary standards and methods, the R_K^{th} values for the thimble chamber give relative information about the procedures used for the calibration of the reference source at each NMI as, in general, each NMI has a different methodology. One outcome of the comparison may be to identify which methods have the lowest uncertainty, what are the most significant sources of uncertainty in each method and also whether these uncertainties arise mainly from the problem of the detector position with respect to the source in this high gradient radiation field.

4.2 Well chamber comparison result

For those NMIs that don't provide a calibration of the thimble chamber, the comparison result will be evaluated using the well chamber measurements; the comparison result R_K^{w} will be expressed as

$$R_K^{\text{w}} = \frac{N_{K,\text{NMI}}^{\text{w}}}{N_{K,\text{BIPM}}^{\text{w}}} \quad (5)$$

where

$N_{K,\text{NMI}}^{\text{w}}$ is the calibration coefficient for the well chamber as defined in 3.4.2 and

$N_{K,\text{BIPM}}^{\text{w}}$ is the mean of the calibration coefficients for the well chamber calculated by the BIPM during the comparisons with the different NMIs, as described in section 3.4.2.

As noted earlier, the results will remain confidential and only the comparison result R_K^{w} will be published in the comparison report.

For the case in which NMIs disseminate RAKR to hospitals through well-chamber calibrations, the degree to which the results for the well chamber are consistent with those for

the thimble chamber (within the combined uncertainties) can provide support for this dissemination in terms of assessing CMCs.

5. Evaluation of the uncertainty and the degrees of equivalence

5.1 Thimble chamber

Each NMI will report the $\dot{K}_{R,NMI}$ and N_K^{th} combined standard uncertainty evaluated according to the “*Guide to the expression of uncertainty in measurement*” (JCGM 100:2008) and will provide a detailed uncertainty budget with references as appropriate.

The N_K^{th} combined standard uncertainty u_{NMIi} should not include a component for the long-term stability of the transfer chamber. The uncertainty due to the stability of the transfer chamber u_{stab} is determined from the BIPM measurements, and the uncertainty for each calibration coefficient is modified to include this component, thus:

$$u_{NMIi,corr}^2 = u_{NMIi}^2 + u_{stab}^2 \quad (6)$$

The comparison result for each NMI is expressed as the ratio R_K^{th} (Eq. 4) with the combined standard uncertainty defined as:

$$u_{i,R_K^{th}}^2 = u_{NMIi,corr}^2 + u_{BIPM}^2 - \sum_n f_n^2 (u_{NMIi,n}^2 + u_{BIPM,n}^2), \quad (7)$$

where the summation contains those components n that are correlated between NMI i and the BIPM, with correlation factor f_n .

5.2 Well chamber

For the well type chamber, the BIPM will evaluate the $N_{K,NMI}^w$ and $N_{K,BIPM}^w$ uncertainties using the NMI and the BIPM uncertainty budgets for the determinations of the RAKR, respectively, and the BIPM uncertainty budget for its measurement system. The uncertainty of the ratio R_K^w is evaluated in the same way as described above for the thimble chamber.

5.3 Degrees of equivalence

For each comparison result $R_{K,i}^{th}$ with combined standard uncertainty u_i , from Eq. (7), the degree of equivalence with respect to the reference value is the difference (Allisy *et al* 2009),

$$D_i = \left(N_{K,NMIi}^{th} - N_{K,BIPM}^{th} \right) / N_{K,BIPM}^{th} = R_{K,i}^{th} - 1 \quad (8)$$

and its expanded uncertainty $U_i = 2 u_i$.

The degree of equivalence of NMI i with respect to each NMI j is the difference,

$$D_{ij} = D_i - D_j = x_i - x_j \quad (9)$$

and its expanded uncertainty $U_{ij} = 2 u_{ij}$, where,

$$u_{ij}^2 = u_{NMIi,corr}^2 + u_{NMIj,corr}^2 - \sum_n f_n^2 (u_{NMIi,n}^2 + u_{NMIj,n}^2) \quad (10)$$

Note that the uncertainty of the BIPM determination does not enter in u_{ij} , although the uncertainty arising from the comparison procedure is included.

6. References

- Allisy P.J., Burns D.T., Andreo P., 2009, International framework of traceability for radiation dosimetry quantities, *Metrologia*, 46(2), S1-S8.
- Chang L., Ho C., Lee J., Y Du and T Chen, 2008, A statistical approach to infer the minimum setup distance of a well chamber to the wall or the floor for ^{192}Ir HDR calibration *Med. Phys.* 35, 2214-2216.
- ICRU 1997, Dose and Volume Specification for Reporting Interstitial Therapy ICRU Report 58 (ICRU: Bethesda, MA).
- JCGM 2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM 1995 with minor corrections) JCGM 100:2008.
- Mainegra-Hing E., Rogers, 2006, On the accuracy of techniques for obtaining the calibration coefficient N_K of ^{192}Ir HDR brachytherapy sources, *Med. Phys.* 33(9), 3340-3347.

Annex A: Reporting form for results of the comparison for Reference Air Kerma Rate for HDR ^{192}Ir , BIPM.RI(I)-K8

<p>Information on source and unit</p> <p>Make of HDR unit</p> <p>Serial number of HDR unit</p> <p>Manufacturer of source</p> <p>Source reference code</p> <p>Apparent activity of source</p> <p>Date of the apparent activity of the source</p>
<p>Well chamber measurements data</p> <p>Date of measurements</p> <p>Details of the primary method used to determine the Reference Air kerma Rate (Reference publication in English will be sufficient if available)</p> <p>Reference air kerma rate on date of measurements</p> <p>Date of measurements for the RAKR</p> <p>Decay correction, $T_{1/2}$ used</p> <p>Combined standard uncertainty associated with the determination of RAKR ($k = 1$)</p> <p><i>Please attach uncertainty budget</i></p> <p>Sweet-spot position as determined by the NMI</p>
<p>Thimble chamber measurements data</p> <p>Date of measurements</p> <p>Method used to calibrate the chamber</p> <p>Set-up description</p> <p>Calibration coefficient N_{RAKR} determined for the chamber corrected for environmental conditions</p> <p>Voltage/polarity applied (outer electrode or collector?)</p> <p>Raw current (no corrections)</p> <p>Distance of measurements</p> <p>Temperature during measurements</p> <p>Pressure during measurements</p> <p>Correction factors applied to the current to calculate N_{RAKR}</p> <p>Humidity during measurements</p> <p>Combined standard uncertainty associated with the determination of calibration coefficient ($k = 1$)</p> <p><i>Please attach the uncertainty budget</i></p>