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NOTE

Comparison of air kerma standards of LNE–LNHB and NPL for ^{192}Ir HDR brachytherapy sources: EUROMET project no 814

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Abstract
An indirect comparison has been made in the air kerma standards for high dose rate (HDR) ^{192}Ir brachytherapy sources at the Laboratoire National Henri Becquerel (LNHB) and the National Physical Laboratory (NPL). The measurements were carried out at both laboratories between November and December 2004. The comparison was based on measurements using well-type transfer ionization chambers and two different source types, Nucletron microSelectron HDR Classic and version 2. The results show the reported calibration coefficients to agree within 0.47% to 0.63%, which is within the overall standard uncertainty of 0.65% reported by both laboratories at the time of this comparison. Following this comparison, some of the NPL primary standard correction factors were re-evaluated resulting in a change of +0.17% in the overall correction factor. The new factor was implemented in May 2006. Applying the revised chamber factor to the measurements reported in this comparison report will reduce the difference between the two standards by 0.17%.

1. Introduction

In Europe, the recommended quantity for the specification of brachytherapy gamma sources is the reference air kerma rate (RAKR), defined by the International Commission on Radiation Units and Measurements (ICRU 1985, ICRU 1997) as the kerma rate to air, in air, at a reference distance of one metre, corrected for air attenuation and scattering. The RAKR can be expressed by the following equation:

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

where $\dot{K}_{\text{air}}(d)$ is the air-kerma-rate measured at a distance d, d (m) is the distance from the centre of the source to the reference point and $d_{\text{ref}} = 1\text{m}$ is the reference distance. The quantity RAKR is expressed in Gy s^{-1} or a multiple of this unit. For cylindrical sources, the direction from the source centre to the reference point shall be at right angles to the long axis of the source.

The two laboratories participating in this comparison have used two different approaches to measure the quantity RAKR. The Laboratoire National Henri Becquerel (LNE–LNHB) is using an interpolation method. The RAKR of the high dose rate (HDR) source is measured with a cavity ionization chamber using a technique originally developed by Goetsch *et al* (1991). Several improvements have been implemented to reduce the uncertainty. The application of this technique is relatively simple and leads to accurate results if a chamber with a flat energy response function is used (Mainegra-Hing and Rogers 2006).

The UK National Physical Laboratory (NPL) has recently established a spherical graphite-walled cavity ionization chamber as primary standard for direct measurement of the source strength of HDR ^{192}Ir brachytherapy sources.

Recently, a bilateral comparison of French and USA brachytherapy dosimetric standards has been conducted between LNE–LNHB and the University of Wisconsin Accredited Dosimetry Calibration Laboratory (UWADCL). The comparison resulted in an excellent agreement between the two laboratories and the measured discrepancies were found to be less than 0.3% (Douysset *et al* 2005). However, both laboratories are using basically the same technique to establish their national standards. NPL uses a different approach and the purpose of this bilateral comparison was to link the new NPL primary standard to the international network of standards for HDR ^{192}Ir sources.

One method of disseminating HDR brachytherapy dosimetric standards to users (radiotherapy centres) is via well-type transfer ionization chambers. The comparison was based on cross calibrations of four of these well chambers.

2. Materials and methods for the definition of dosimetric standards

2.1. Radiation sources

The NPL uses a Nucletron microSelectron HDR Classic brachytherapy unit fitted with the 'Classic' source, part number 096.001, whereas LNE–LNHB uses a Nucletron microSelectron HDR V2 unit fitted with the most recently designed source, part number 105.002. Both sources are manufactured by Mallinckrodt Medical B V (The Netherlands). The sources are made of pure ^{192}Ir cylinders of slightly different lengths (3.5 mm and 3.6 mm) and diameters (0.60 mm and 0.65 mm) for the 'Classic' and 'V2' source, respectively. The sources are surrounded by an AISI 316 L stainless steel encapsulation (radial thicknesses: 250 μm for the 'Classic' source and 125 μm for the 'V2' model). The stainless steel capsules are welded to a metal plug and a 1500 mm long stainless steel cable (see figures 1 and 2). The nominal initial activity of both sources is 370 GBq. The averaged RAKR of the NPL source used for the comparison was 36 mGy h^{-1} at 1 m. The averaged RAKR of the LNE–LNHB source used for the comparison was 29 mGy h^{-1} at 1 m.

Emission anisotropy is the major difference between sources. Even though the average photon energy is relatively high (close to 400 keV), due to the very high density of iridium, the self-absorption of photons along the source longitudinal axis is significant. Thus, air-kerma-rate is a function of the polar angle relative to the transverse plane. During source calibration, anisotropy is not taken into account since the averaging angles are in all cases less than 5°. However, with well-type chambers the averaging angles increase typically up

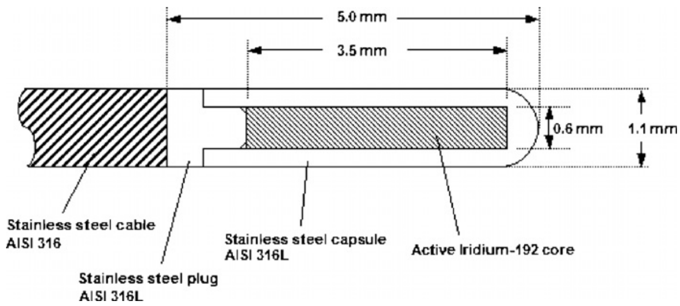

Figure 1. Schematic drawing of the Nucletron 'Classic' ^{192}Ir HDR brachytherapy source.

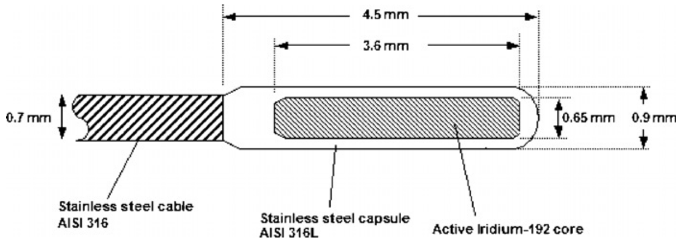

Figure 2. Schematic drawing of the Nucletron 'V2' ^{192}Ir HDR brachytherapy source.

to 70°. Therefore, differences in emission anisotropy influence only the well-type chamber measurements. A preliminary study has been launched at LNE–LNHB to estimate by Monte Carlo simulation the influence of the source design on the well-type chamber calibration coefficient. The `MCNP4C` (Breismeister 2000) code (cross-section libraries: `MCPLIB02` and `EL03` for photons and electrons, respectively) has been used in order to estimate the following ratio:

$$N = \frac{K_{\mathrm{air}}(d)}{E_{\mathrm{air}}}, \qquad (2)$$

where K_{air} denotes the air kerma at distance d and 0° angle and is deduced from simulated photon fluence at distance d. E_{air} is the energy deposited in the air of the well-type ionization chamber cavity.

N, as defined in (2), was determined for all combinations of the two different source designs and the two types of well-type chambers used in this comparison. The ratio of different values of N was found to be ranging from 1.0013(23) to 1.0024(23).

The Monte Carlo determination of the energy deposited in the air of an ionization chamber cavity is known to be a difficult process, therefore the code has to be benchmarked. A simulation of the axial response curve of the detector—which is proportional to the deposited energy—has been performed. The experimental shape of the curve could be reproduced with discrepancies lower than 0.25% giving confidence in the results presented above.

Therefore according to our present knowledge, the use of different source and chamber designs should have no observable effect (within the quoted uncertainties), on the measured degree of equivalence of the two dosimetric standards.

2.2. ^{192}Ir HDR source calibration in terms of RAKR at LNE–LNHB

An indirect method is used by LNE–LNHB to determine the RAKR of HDR brachytherapy sources. This method has been described elsewhere (Douysset *et al* 2005). Only the main steps are recalled in this note.

$\dot{K}_R$ is measured with a cavity ionization chamber. The calibration coefficient of this chamber for the ^{192}Ir spectrum is determined by interpolation from x-rays (250 kVp), ^{137}Cs and ^{60}Co. The calibrations of the chamber have been performed in the national reference beams of ^{137}Cs and ^{60}Co at the LNE–LNHB. Since the laboratory was at the time of the comparison in the process of developing a primary standard for x-rays, x-ray calibrations of the cavity chamber have been performed by BIPM.

A NE2571 chamber with a nominal volume of 0.6 cm^3 has been used. This chamber combines two advantages: first, a very low energy dependence across the energy range of ^{192}Ir photons making the interpolation technique more valid; second, a very good long-term stability (relative change of the calibration coefficient close to 0.1% over four years).

A linear interpolation between two points is performed to estimate the calibration coefficient of the chamber at the mean energy of ^{192}Ir. Two different methods can be used: interpolation between x-rays and ^{137}Cs or between x-rays and ^{60}Co. A very good agreement between the two calibration coefficients is obtained. Owing to the smaller uncertainty, the interpolation between x-rays and ^{137}Cs is used.

LNE–LNHB is using the interpolation method recommended by IAEA (see IAEA (1999, 2002)). As suggested by Mainegra-Hing and Rogers (2006), averaging of $(1/N_K)$ values is more correct. Furthermore, no corrections for the wall effect are necessary. However, in the present case, the application of this method would lead to a negligible change ($< 0.02\%$).

The RAKR of a brachytherapy source is estimated using the following equation:

$$\dot{K}_R = N_K(\mathrm{Ir}) \cdot I \cdot \prod_i k_i \cdot \left(\frac{d}{d_{\mathrm{ref}}}\right)^2, \tag{3}$$

where $\prod_i k_i = k_N \cdot k_{\mathrm{att}} \cdot k_{\mathrm{scatt}}$, $N_K(\mathrm{Ir})$ denotes the interpolated calibration coefficient for the ^{192}Ir spectrum, I is the current measured by the ionization chamber (corrected for radioactive decay, atmospheric conditions, collection efficiency and polarity effects) and k_i are the correction factors (for non-uniformity, attenuation and scattering effects).

Details about the experimental set-up can be found in Douysset *et al* (2005).

2.2.1. Correction factors. Equation (3) shows several correction factors which have to be taken into account. Because of the high dose gradient around the source and the relatively large dimensions of the ionization chamber, there is a strong photon fluence variation over the surface of the ionization chamber. This phenomenon leads to a non-uniform electron fluence in the chamber in both radial and azimuthal directions. This can be corrected using the theoretical calculations of Kondo and Randolph (1960) and Bielajew (1990). This correction depends both on the distance and the ionization chamber geometry. For the NE2571 chamber, it is relatively large (about 1% at 100 mm).

The measurement of RAKR requires to account for the beam attenuation and scattering due to the source holder and to the air between the source and the detector. This correction is deduced from Monte Carlo simulations. Due to the competing effects of scattering and attenuation, both corrections largely compensate each other, so the product of these correction factors remains almost constant over the measurement range (100–225 mm) and was found to be approximately equal to 1.004.

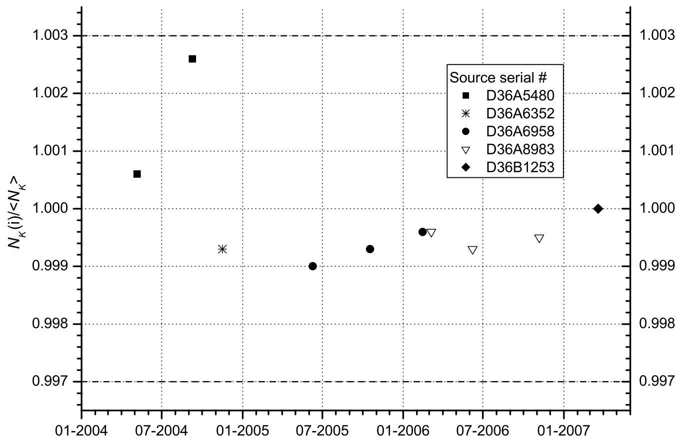

Figure 3. Calibration history of the LNE–LNHB HDR1000+/MAX4000 dosimeter. The calibration coefficients were determined using five different Nucletron microSelectron V2 HDR ^{192}Ir sources between 2004 and 2007 and normalized to the running mean.

Finally, RAKR is defined in an infinite medium, and in the absence of scattered radiation from any source. Therefore, the room-related scatter contribution has to be measured and subtracted from the signal. The multiple distance technique has been used. Once the source-to-detector distance is precisely measured, this distance is increased and the current is recorded. Usually five to ten points are measured. By solving equation (4) (two unknowns), one can deduce precisely the current due to scattering, I_{scatt} (supposed to be constant over short distances):

$$I_{\text{meas}}(d) - I_{\text{back}} = I_{\text{scatt}} + \frac{\alpha}{d^2} \cdot \frac{1}{k_N(d) \cdot k_{\text{att}}(d)}, \tag{4}$$

where I_{back} is the background current (i.e. measured without any radioactive source), α is a constant, d is the source-to-detector distance, $k_N(d)$ is the non-uniformity correction factor and $k_{\text{att}}(d)$ is the beam attenuation correction factor. Typically, I_{scatt} represents about 0.25% of the measured current at 100 mm.

2.2.2. Uncertainty budget. The total uncertainty of the source calibration at LNE–LNHB is 1.2% ($k = 2$).

2.2.3. Practical considerations. At LNE–LNHB a new ^{192}Ir source is loaded in the afterloader every year. Every time the source RAKR is determined twice using the above technique. A maximum discrepancy of 0.3% between the determinations is tolerated. Two well-type chambers and an associated electrometer are also periodically calibrated (see figure 3). As a constancy check, prior to issuing a new source certificate, the deviations of the calibration coefficients are confirmed to be within the tolerance. A maximum deviation of 0.3% from the running mean is accepted after a source exchange.

2.3. ^{192}Ir HDR source calibration in terms of RAKR at NPL

The UK national air kerma standard for ^{192}Ir gamma rays is the response of the NPL primary standard cavity chamber TH100C. The spherical cavity volume was measured on two coordinate measuring machines and found to be 102.519 cm^3. From this measurement the mass of air in the collecting volume was determined. The wall thickness was measured using a similar technique. The wall of the cavity chamber is made of high-purity graphite ($\rho = 1.75$ g cm^{-3}). Photon dosimetry requires that an ionization chamber's wall thickness must be sufficient to provide charged particle equilibrium (CPE) for the highest energy of secondary electrons present. In the case of ^{192}Ir, this requires a wall thick enough to stop 687 keV Compton recoil electrons generated by 885 keV gamma rays, the most energetic photons emitted by ^{192}Ir (Goetsch *et al* 1991), neglecting three very weak lines above 1 MeV. The CSDA (continuous slowing down approximation) range of 687 eV electrons is 0.31 g cm^{-2} of graphite (ICRU 1984), which is equivalent to a wall thickness of approximately 1.8 mm. The graphite wall of the cavity chamber is between 3.5 mm and 4 mm thick, i.e. there is sufficient build-up material in the chamber wall to provide CPE. The NPL cavity chamber TH100C is a guarded ionization chamber, resulting in low leakage currents and post-irradiation effects and is described in detail in NPL report DQL-RD 004 (Sander and Nutbrown 2006).

2.3.1. The measurement set-up. The experimental set-up for the measurement of reference air kerma rate of an HDR ^{192}Ir brachytherapy source under minimal scattering conditions at a centre-to-centre source–chamber distance of 1433 mm is shown in figure 4. A lead collimator was designed for use with the HDR brachytherapy source for the following two reasons: (1) to avoid irradiating any air cavities inside the chamber stem and the connectors, which would have resulted in generating an unknown leakage current and (2) to reduce the amount of scattered radiation from the floor and the walls of the exposure room reaching the collecting volume of the cavity chamber and therefore keeping the scatter correction as small as possible. The front wall of the lead collimator is 7.5 cm thick and contains a centred 2 cm diameter conical aperture. The other five walls are 4 cm thick. The internal dimensions are: 40 cm length, 30 cm width and 30 cm height. The HDR ^{192}Ir source is set up inside the lead collimator perpendicular to the long central axis, 10 cm away from the back wall. The collimated gamma-ray beam is directed towards the primary standard cavity chamber. The source-to-chamber distance and aperture size were chosen to give a uniform field over the whole graphite sphere of the ionization chamber. The gamma-ray beam is circular in cross section.

2.3.2. The measurement equation. The determination of RAKR using this chamber relies on the application of Bragg–Gray and large cavity theory. Deviations from the Bragg–Gray cavity theory have been accounted for by applying an electron fluence perturbation correction factor as shown in equation (5). The following measurement equation applies to the NPL primary standard chamber and shows how the RAKR of an HDR ^{192}Ir source is determined from the measured ionization current:

$$\dot{K}_R = \frac{I_{\mathrm{corr}} \cdot k_{\mathrm{elec}}}{\rho_{\mathrm{air}} \cdot V_{\mathrm{air}}} \cdot \left(\frac{W_{\mathrm{air}}}{e}\right) \cdot \frac{1}{(1-\bar{g})} \cdot \left(\frac{\bar{S}}{\rho}\right)^{\mathrm{graph}}_{\mathrm{air}} \cdot k_{\mathrm{fl}} \cdot \left(\frac{\bar{\mu}_{\mathrm{en}}}{\rho}\right)^{\mathrm{air}}_{\mathrm{graph}} \cdot \prod_i k_i \cdot \left(\frac{d}{d_{\mathrm{ref}}}\right)^2 \cdot (k_{\mathrm{air}} \cdot k_{\mathrm{ion}} \cdot k_{\mathrm{dec}} \cdot k_h \cdot k_{Tp}), \tag{5}$$

where

- $\dot{K}_R$ is the RAKR (Gy s^{-1}) at the chosen reference time t_{ref},
- I_{corr} is the displayed ionization current (A) on the electrometer corrected for leakage,
- k_{elec} is the electrometer correction factor,
- $V_{\mathrm{air}} = 1.02519 \times 10^{-4}$ m^3 is the cavity volume,

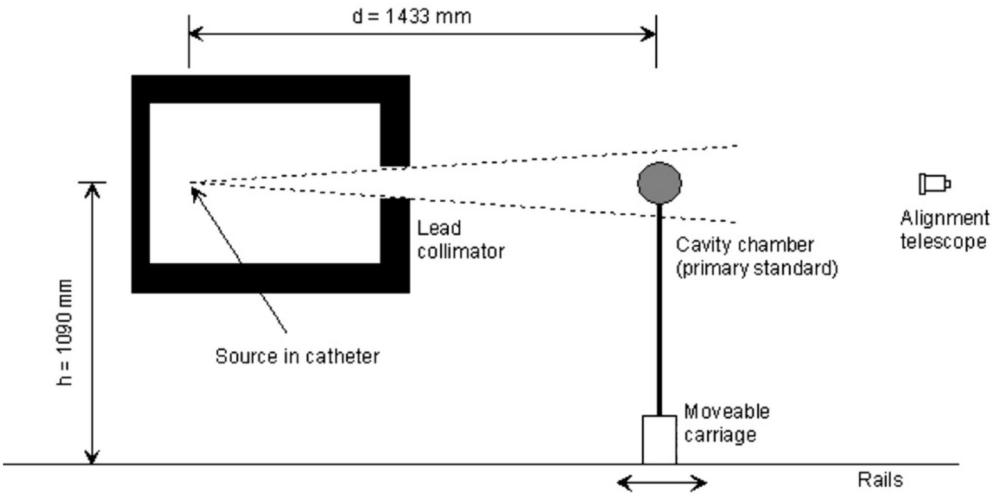

Figure 4. Side view of the set-up for ^{192}Ir HDR source calibrations at NPL (not to scale). The ^{192}Ir source is placed inside a lead collimator producing a collimated photon beam which does not impinge on the floor. For source calibrations at NPL, the cavity chamber is set up at a centre-to-centre source–chamber distance of 1433 mm.

- $\rho_{air} = 1.2045$ kg m^{-3} is the density of dry air at normal pressure and temperature (Davis 1992),
- W_{air} is the average energy (J) spent by an electron of charge e (C) to produce an ion pair in dry air, where $\left(\frac{W_{air}}{e}\right) = 33.97 \pm 0.05$ J C^{-1} (Boutillon and Perroche-Roux 1987),
- $\bar{g} = 0.0006$ is the fraction of secondary electron energy lost to bremsstrahlung in air (determined by the Monte Carlo simulation),
- $\left(\frac{\bar{S}}{\rho}\right)^{graph}_{air} \cdot k_{fl} = 1.0082$ 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 the Monte Carlo simulation),
- $\left(\frac{\bar{\mu}_{en}}{\rho}\right)^{air}_{graph} = 1.0017$ is the ratio of the mean photon-energy-fluence-weighted photon mass energy-absorption coefficient of air to that of graphite (determined by the Monte Carlo simulation),
- $\prod_i k_i$ is the product of six correction factors, i.e. stem scatter and polarity correction (determined by measurement) and wall correction, central electrode correction, axial and radial non-uniformity correction (determined by the Monte Carlo simulation),
- $\left(\frac{d}{d_{ref}}\right)^2$ normalizes the current measured at centre-to-centre source–chamber distance $d = 1.433$ m (see figure 4) to the reference distance $d_{ref} = 1$ m,
- k_{air} is the combined air attenuation and scatter correction which corrects the measured current for air attenuation and scatter between the source and the point of measurement,
- k_{ion} is the ion recombination correction factor (assumed to be unity at the time of this comparison),
- k_{dec} is the decay correction to a chosen reference time with $\tau_{1/2} = (73.822 \pm 0.009)$ days (Woods *et al* 2004)),
- $k_h = 0.9970$ is the humidity correction factor (Rogers and Ross 1988),
- k_{Tp} is the temperature and pressure correction.

When secondary standard ionization chambers are calibrated with the calibrated source, the ionization current is corrected to the same reference time before the calibration coefficient

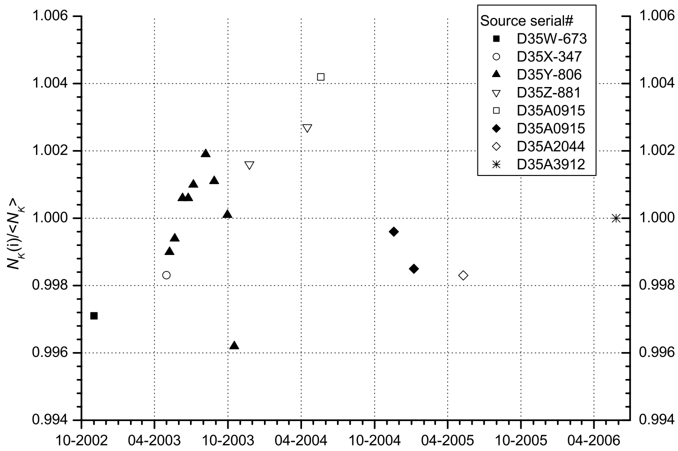

Figure 5. Calibration history of the NPL HDR1000+ ionization chamber. The calibration coefficients were determined using eight different Nucletron microSelectron Classic HDR ^{192}Ir sources between 2002 and 2006 and normalized to the running mean.

(primary standard to secondary standard ratio) is calculated. A combined air attenuation and air scatter correction is applied to the measured ionization current which accounts for the fact that the RAKR measurements are made in air. The correction factor was determined by applying the multiple distance method as described by Sander and Nutbrown (2006). The ionization currents were measured at distances between 1.2 m and 4 m at 0.2 m intervals and the corrected readings were normalized to the reference distance of 1 m by applying the inverse-square law. The variation of the normalized currents with the source-to-chamber distance was found to be linear. For the measurement distance of 1.433 m, the combined air attenuation and scatter correction is $I_{\text{ion}}(0\ \text{m})/I_{\text{ion}}(1.433\ \text{m})$ and was found to be equal to 1.016.

2.3.3. Source calibration. After setting up the lead collimator and the cavity chamber (see section 2.3.1), the brachytherapy source was stepped through the catheter inside the lead collimator, while the centre of the graphite sphere of the ionization chamber remained stationary on the central beam axis and the measured ionization current was plotted against the dwell position of the source. For the source calibration, the dwell position corresponding to the middle of the plateau was chosen. Finally, a radiograph was taken to check the alignment and to ensure the graphite sphere was fully covered by the primary beam. The ionization current collected with the primary standard chamber was measured with a calibrated electrometer. At least five measurements of the ionization current were taken. The reference air kerma rate of the ^{192}Ir source in terms of mGy h^{-1} was determined by applying equation (5).

The total uncertainty of the source calibration at NPL is 1.2% ($k = 2$). Figure 5 shows the calibration history of a well chamber owned by NPL which was used for this comparison and which is routinely used as reference chamber.

3. Materials and methods for the comparison

3.1. Materials

The present comparison has been conducted with four well-type chambers (two belonging to LNE–LNHB and two to NPL). Two models of well-type chambers have been calibrated: PTW

Model TW33004[3] and Standard Imaging Model HDR1000+. The chambers were connected to PTW and Standard Imaging medical-type electrometers.

3.2. Methods

The well chamber was positioned at least 1 m from any wall and 1 m above the floor level on a low scatter surface. Before commencing measurements, sufficient time was allowed for the chamber to reach thermal equilibrium with the surrounding air. The well chamber was connected to a calibrated electrometer. Measurements were taken after a warm-up period of at least 30 min in which time the electrometer, ionization chamber and cables were allowed to settle. The leakage current was measured prior to the calibration and found to be less than 0.01% of the measured ionization current in all cases, i.e. the readings were not corrected for leakage. Since the chambers were vented to air, all measured ionization currents were normalized to standard atmospheric conditions: $T_0 = 293.15$ K, $p_0 = 101.325$ kPa and $RH_0 = 50\%$. Calibrated instruments were used to record atmospheric parameters. No humidity correction was applied. As pointed out by Poirier and Douysset (2006), humidity variations may significantly affect the calibration coefficients of well-type chambers. However, the present work has been conducted under similar humidity conditions.

The point of maximum response of the chamber was found by stepping the ^{192}Ir source through the chamber and by plotting the corrected ionization current versus the dwell position of the source. The ^{192}Ir source was then sent to the dwell position corresponding to the maximum chamber response and at least five measurements of the ionization current were taken.

The calibration coefficients issued by LNE–LNHB are expressed as mGy h^{-1}(1 m) unit^{-1} of reading (1 min integration). The calibration coefficients are obtained by LNE–LNHB using the following equation:

$$N_{\dot{K}_R} = \frac{\dot{K}_R(0) \cdot \Delta t}{k_{\mathrm{dec}}(t) \cdot R(t) \cdot k_{\mathrm{ion}}}, \tag{6}$$

where $\dot{K}_R(0)$ denotes the source RAKR measured during the source calibration, Δt is equal to 1 min (as displayed by the electrometer), $k_{\mathrm{dec}}(t)$ is the decay correction between the source-calibration and the well-chamber calibration, $R(t)$ is the electrometer reading in charge mode (corrected for atmospheric effects) and $k_{\mathrm{ion}} = (A_{\mathrm{ion}})^{-1}$ is the inverse of the charge collection efficiency.

Decay correction is calculated by LNE–LNHB using the following half-life: (73.827 ± 0.013) days (DDEP 2004). This value is slightly different from the one used by NPL. However, this difference will not lead to any substantial effect on the results of the comparison.

The calibration coefficients issued by NPL are expressed as Gy C^{-1}. The calibration coefficients are obtained by NPL using the following equation:

$$N_{\dot{K}_R} = \frac{\dot{K}_R(0)}{k_{\mathrm{dec}}(t) \cdot I(t)}, \tag{7}$$

where $\dot{K}_R(0)$ is the RAKR of the calibrated source, $I(t)$ is the corrected ionization current (A) including the calibration factor for the electrometer and $k_{\mathrm{dec}}(t)$ is the decay correction to the reference time, t_{ref}. At the time of the comparison, commercial calibrations at NPL did not include a recombination correction, however, in order to compare the calibration coefficients determined by both laboratories, the following corrections were applied to the reported values:

[3] Equivalent to Nucletron Model 077.091.

Table 1. Uncertainty budget for a typical routine well-type chamber calibration (LNE–LNHB).

	Value	Relative standard uncertainty (%) Type A	Type B
$\dot{K}_R(0)$ (mGy h^{-1}(1m))	38.22	–	0.60
R(1min) (nC)	3315.7	<0.01	0.16
k_{dec}	1.4957	–	<0.01
k_{ion}	1.0006	<0.01	0.03
Combined standard uncertainty		0.62	
Expanded uncertainty ($k = 2$)		1.3	

Table 2. Uncertainty budget for a typical routine well-type chamber calibration (NPL).

	Value	Relative standard uncertainty (%) Type A	Type B
$\dot{K}_R(0)$ (mGy h^{-1}(1m))	40.75	–	0.58
I (nA)	60.0	<0.01	0.28
k_{dec}	1.5258	–	<0.01
Combined standard uncertainty		0.64	
Expanded uncertainty ($k = 2$)		1.3	

- The recombination correction factor, k_{ion}, was determined using the two-voltage technique (Attix 1984) and applied to the calibration coefficient calculated in equation (7) by dividing by k_{ion}. Since the collection efficiency depends on the source activity, a direct comparison of obtained k_{ion} values would not be relevant.
- The units of the calibration coefficients reported by LNE–LNHB in terms of mGy h^{-1}(1 m) unit^{-1} of reading (1 min integration) were converted to Gy C^{-1} and the displayed reading of charge was corrected by applying the electrometer calibration factor. The electrical calibration of the LNE–LNHB electrometer was performed at LNE and the electrical calibration of both NPL electrometers was performed at NPL.

The calibration coefficients are given by both laboratories for the user's required polarity. However, the bias polarity correction, k_{pol}, is estimated using the following equation:

$$k_{\text{pol}} = \frac{I^+ + I^-}{2 \cdot I^+}. \tag{8}$$

Here, I^+ and I^- represent the measured currents for +300 V and − 300 V bias.

3.3. Uncertainty budgets

Uncertainties associated with the point of maximum response determinations are estimated by both participants to 1.5 mm. Typical uncertainty budgets for commercial calibrations are summarized in tables 1 and 2.

As mentioned earlier for the purpose of this comparison, LNE–LNHB calibration coefficients are corrected to account for electrical calibration of the electrometer. The standard uncertainty associated with the correction factor is 0.1% leading to an increase in the overall calibration uncertainties of less than 0.01%. In the same way, the calibration coefficients issued

Table 3. Comparison of calibration coefficients (unit: $\times 10^2$ Gy C^{-1}).

Chamber Electrometer	Serial Number	LNE–LNHB (standard uncertainty)	NPL (standard uncertainty)	Ratio
Nucletron 077.091 Std. Imaging MAX4000	25324 E040491	2.592 ± 0.017	2.580 ± 0.017	1.0047
Std. Imaging HDR1000+ Std. Imaging MAX4000	A002231 E040491	1.285 ± 0.008	1.278 ± 0.008	1.0055
Std. Imaging HDR1000+ Std. Imaging CDX-2000A	A961699 B961801	1.286 ± 0.008	1.278 ± 0.008	1.0063
PTW TW33004 PTW Unidos 10002	0031 20487	2.513 ± 0.016	2.501 ± 0.016	1.0048

by NPL are corrected for the recombination efficiency. For the same reason, this correction has a negligible impact on the calibration uncertainties.

4. Results

All calibrations were performed between November and December 2004. Upon return of the instruments, constancy checks of the systems have been conducted by participants. Measured relative changes were in all cases less than 0.1%.

The agreement for the point of maximum response determinations has been found to be in the order of ± 1 mm leading to a negligible influence on calibration coefficients. Both participants agreed on the fact that bias polarity effects are negligible for Standard Imaging chambers and in the order of 1.002 for PTW/Nucletron chambers.

For each transfer chamber, the ratio of the calibration coefficients $N_{K,\mathrm{LNHB}}/N_{K,\mathrm{NPL}}$ was evaluated. The final results of this comparison are given in table 3.

Following this comparison, a thorough re-evaluation of the following correction factors of the NPL primary standard cavity chamber for ^{192}Ir has been carried out: electron energy lost to bremsstrahlung, product of the stopping power ratio (graphite to air) and the fluence perturbation correction factor, mass energy–absorption coefficient ratio (air to graphite), wall correction, central electrode correction and non-uniformity correction (all determined by the Monte Carlo simulation) and corrections for stem scatter, ion recombination and polarity (all determined experimentally). Following the re-evaluation, the new overall chamber factor has changed by +0.17% and the new values and the description of how the work was carried out can be found in an NPL report (Sander and Nutbrown 2006).

Table 4 shows the likely results of this comparison if the new factors had been used, leading to a better agreement between the reported calibration coefficients. The new correction factor was implemented at NPL in May 2006 and a revised uncertainty analysis table was written following the recommendations given in the guide to the expression of uncertainty in measurement (ISO 1995). All well chamber calibration coefficients reported by NPL after May 2006 are based on the revised primary standard chamber factor and the standard uncertainty in the well chamber calibration coefficient has been reduced to 0.37%.

Table 4. Comparison of revised calibration coefficients. The NPL calibration coefficients and uncertainties shown in this table were calculated using the re-evaluated primary standard correction factors and the revised measurement uncertainties (post-May 2006 values). The values listed below indicate what the likely result of this comparison would have been if the new correction factors would have been used (unit: $\times 10^2$ Gy C^{-1}).

Chamber Electrometer	Serial Number	LNE–LNHB (standard uncertainty)	NPL (standard uncertainty)	Ratio
Nucletron 077.091 Std. Imaging MAX4000	25324 E040491	2.592 ± 0.017	2.584 ± 0.010	1.0030
Std. Imaging HDR1000+ Std. Imaging MAX4000	A002231 E040491	1.285 ± 0.008	1.280 ± 0.005	1.0038
Std. Imaging HDR1000+ Std. Imaging CDX-2000A	A961699 B961801	1.286 ± 0.008	1.280 ± 0.005	1.0046
PTW TW33004 PTW Unidos 10002	0031 20487	2.513 ± 0.016	2.505 ± 0.010	1.0031

5. Conclusions

The comparison of the transfer chambers has shown a good agreement of the two HDR ^{192}Ir brachytherapy source calibration techniques established at the LNE–LNHB and the NPL. The ratio of calibration coefficients $N_{K,\mathrm{LNHB}}/N_{K,\mathrm{NPL}}$ was found to be between 1.0047 and 1.0063 which is within the overall standard uncertainty of 0.65%, and with the new NPL primary standard correction factors the ratio of the calibration coefficients would likely to be between 1.0030 and 1.0046.

The work presented in this note and the bilateral comparison between LNE-LNHB and UWADCL (Douysset *et al* 2005) show that the French, UK and USA national air kerma standards for HDR ^{192}Ir brachytherapy sources are in good agreement.

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References

Attix F H 1984 Determination of A_{ion} and P_{ion} in the new AAPM radiotherapy dosimetry protocol *Med. Phys.* **11** 714–6

Bielajew A F 1990 Correction factors for thick-walled ionisation chambers in point-source photon beams *Phys. Med. Biol.* **35** 501–16

Boutillon M and Perroche-Roux A M 1987 Re-evaluation of the W for electrons in dry air *Phys. Med. Biol.* **32** 213–9

Breismeister J F 2000 MCNP a general Monte Carlo *N*-particle transport code—version 4C, Los Alamos National Laboratory *Manual LA-13709-M*

Davis R S 1992 Equation for the determination of the density of moist air (1981/91) *Metrologia* **29** 67–70

Decay Data Evaluation Project (DDEP) 2004 LNE–CEA/LNHB (France), PTB (Germany), INEEL (USA), KRI (Russia), LBNL (USA), NPL (United Kingdom), CIEMAT (Spain) http://www.nucleide.org/DDEP.htm

Douysset G, Gouriou J, Delaunay F, DeWerd L, Stump K and Micka J 2005 Comparison of dosimetric standards of USA and France for HDR brachytherapy *Phys. Med. Biol.* **50** 1961–78

Goetsch S J, Attix F H, Pearson D W and Thomadsen B R 1991 Calibration of ^{192}Ir high-dose-rate afterloading systems *Med. Phys.* **18** 462–7

IAEA 1999 Calibration of brachytherapy sources. Guidelines of standardized procedures for the calibration of brachytherapy sources at secondary standard dosimetry laboratories (SSDLs) and hospitals *TECDOC–1079* (Vienna)

IAEA 2002 Calibration of photon and beta ray sources used in brachytherapy *TECDOC–1274* (Vienna)

ICRU 1985 Dose and Volume Specification for Reporting Intracavitary Therapy in Gynecology *ICRU Report No 38* (Washington, DC: ICRU)

ICRU 1997 Dose and Volume Specification for Reporting Interstitial Therapy *ICRU Report No 58* (Bethesda, MD: ICRU)

ISO 1995 *Guide to the Expression of Uncertainty in Measurement* (Geneva: International Organization for Standardization)

Kondo S and Randolph M L 1960 Effect of finite size of ionization chambers on measurements of small photon sources *Radiol. Res.* **13** 37–60

Mainegra-Hing E and Rogers D W O 2006 On the accuracy of techniques for obtaining the calibration coefficient N_K of ^{192}Ir HDR brachytherapy sources *Med. Phys.* **33** 3340–7

Poirier A and Douysset G 2006 Influence of ambient humidity on the current delivered by air-vented ionization chambers revisited *Phys. Med. Biol.* **51** 4995–5006

Rogers D W O and Ross C K 1988 The role of humidity and other correction factors in the AAPM TG-21 dosimetry protocol *Med. Phys.* **15** 40–8

Sander T and Nutbrown R F 2006 The NPL air kerma primary standard TH100C for high dose rate ^{192}Ir brachytherapy sources *NPL Report DQL-RD 004* ISSN 1744-0637 (Teddington, UK) http://publications.npl.co.uk

Woods M J, Collins S M and Woods S A 2004 Evaluation of half-life data *NPL Report CAIR 8*, ISSN 1740-0953 (Teddington, UK)