Key comparison BIPM.RI(I)-K7 of the air-kerma standards of the ENEA-INMRI, Italy and the BIPM in mammography x-rays

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Abstract

A first key comparison has been made between the air-kerma standards of the ENEA-INMRI, Italy and the BIPM in mammography x-ray beams. The results show the standards to be in agreement at the level of the standard uncertainty for the comparison of 4.8 parts in 10^3. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

An indirect comparison has been made between the air-kerma standards of the Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti (INMRI) of the Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (ENEA), Italy and the Bureau International des Poids et Mesures (BIPM) in the W/Mo mammography beams in the x-ray range from 23 kV to 35 kV. A thin-window parallel-plate ionization chamber was used as a transfer instrument. The measurements at the BIPM took place in April 2014 using the reference conditions recommended by the CCRI and described by Allisy *et al* (2011). Supporting measurements at the ENEA-INMRI continued until March 2015. To verify the stability of the transfer instrument, additional measurements were done at the BIPM when the ENEA supplied the final results in April 2015.

2. Determination of the air-kerma rate

For a free-air ionization chamber standard with measuring volume V, the air-kerma rate is determined by the relation

$$\dot{K} = \frac{I}{\rho_{\text{air}} V} \frac{W_{\text{air}}}{e} \frac{1}{1 - g_{\text{air}}} \prod_i k_i \qquad (1)$$

where ρ_{air} is the density of air under reference conditions, I is the ionization current under the same conditions, W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in air, g_{air} is the fraction of the initial electron energy lost through radiative processes in air, and $\Pi\, k_{\text{i}}$ is the product of the correction factors to be applied to the standard.

The values used for the physical constants ρ_{air} and W_{air}/e are given in Table 1. For use with this dry-air value for ρ_{air}, the ionization current I must be corrected for humidity and for the difference between the density of the air of the measuring volume at the time of measurement and the value given in the table.[1]

[1] For an air temperature T around 293 K, pressure P and relative humidity around 50 % in the measuring volume,

Table 1. Physical constants used in the determination of the air-kerma rate

Constant	Value	u_i [a]
ρ_{air} [b]	1.2930 kg m^{-3}	0.0001
W_{air} / e	33.97 J C^{-1}	0.0015

[a] u_i is the relative standard uncertainty.
[b] Density of dry air at T_0 = 273.15 K and P_0 = 101.325 kPa.

3. Details of the standards

Both free-air chamber standards are of the conventional parallel-plate design. The measuring volume V is defined by the diameter of the chamber aperture and the length of the collecting region. The BIPM air-kerma standard is described by Boutillon *et al* (1969); the correction factors for the mammography qualities are described by Kessler (2006) and the changes made to certain correction factors, by Burns *et al* (2009). A description of the ENEA-INMRI CAL02 standard can be found in the report of the direct comparison carried out at the BIPM in the W/Al low-energy x-ray beams (Burns *et al* 2011). The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	ENEA-INMRI
Aperture diameter / mm	9.941	8.014
Air path length / mm	100.0	65.12
Collecting length / mm	15.466	40.738
Electrode separation / mm	70	60
Collector width / mm	71	60
Measuring volume / mm^3	1 200.4	2 054.9
Polarizing voltage / V	+1 500	+1 600

4. The transfer instrument

4.1 Determination of the calibration coefficient for a transfer instrument

The air-kerma calibration coefficient N_K for a transfer instrument is given by the relation

$$N_K = \frac{\dot{K}}{I_{tr}} \qquad (2)$$

where $\dot{K}$ is the air-kerma rate determined by the standard using (1) and I_{tr} is the ionization current measured by the transfer instrument and the associated current-measuring system. The

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the correction for air density involves a temperature correction T / T_0, a pressure correction P_0 / P and a humidity correction k_h = 0.9980. At the BIPM, the factor 1.0002 is included to account for the compressibility of dry air between T around 293 K and T_0 = 273.15 K.

current I_{tr} is corrected to the reference conditions of ambient air temperature, pressure and relative humidity chosen for the comparison (T = 293.15 K, P = 101.325 kPa and h = 50 %).

To derive a comparison result from the calibration coefficients $N_{K,\mathrm{BIPM}}$ and $N_{K,\mathrm{NMI}}$ measured, respectively, at the BIPM and at a national measurement institute (NMI), differences in the radiation qualities must be taken into account. Normally, each quality used for the comparison has the same nominal generating potential at each institute, but the half-value layers (HVLs) might differ. A radiation quality correction factor k_Q is derived for each comparison quality Q. This corrects the calibration coefficient $N_{K,\mathrm{NMI}}$ determined at the NMI into one that applies at the 'equivalent' BIPM quality and is derived by interpolation of the $N_{K,\mathrm{NMI}}$ values in terms of HVL. The comparison result at each quality is then taken as

$$R_{K,\mathrm{NMI}} = \frac{k_Q N_{K,\mathrm{NMI}}}{N_{K,\mathrm{BIPM}}} \qquad (3)$$

For the present comparison, this is discussed in section 7.2.

4.2 Details of the transfer instrument

A thin-window parallel-plate ionization chamber belonging to the ENEA-INMRI was used as the transfer instrument for the comparison. Its main characteristics are given in Table 3. The reference point for the chamber was taken to be on the axis defined by the entrance window (passing through the centre of the entrance window). The reference plane for the chamber is defined by the red line around the body of the chamber.

Table 3. Main characteristics of the transfer chamber

Chamber type	Radcal RC6M
Serial number	10206
Window material	metallized polyester
Window thickness / mg cm^{-2}	0.7
Collector diameter / mm	30
Cavity height / mm	8.5
Nominal volume / cm^3	6.0
Polarizing potential [a] / V	+300

[a] Potential applied to the chamber window, the collector remaining at virtual ground potential.

5. Calibration at the BIPM

5.1 The BIPM irradiation facility and reference radiation qualities

The BIPM low-energy x-ray laboratory houses a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 1 mm beryllium. A molybdenum filter of thickness 60 µm is added for all radiation qualities. A voltage divider is used to measure the generating potential, which is stabilized using an additional feedback system designed at the BIPM. Rather than use a transmission monitor, the anode current is measured and the ionization chamber current is normalized for any deviation from the reference anode current. The resulting variation in the BIPM FAC-L-01 free-air chamber current over the duration of a comparison is normally not more than 3×10^{-4} in relative terms. The radiation qualities used in the range from 23 kV to 35 kV are given in Table 4 in ascending order, from left to right, of the half-value-layer (HVL) measured using aluminium filters.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 0.2 °C. Two thermistors, calibrated to a few mK, measure the temperature of the ambient air and the air inside the BIPM standard. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range 47 % to 53 % and consequently no humidity correction is applied to the current measured using transfer instruments.

Table 4. Characteristics of the BIPM mammography radiation qualities

Radiation quality	W/Mo-23	W/Mo-28	W/Mo-30	W/Mo-35
Generating potential / kV	23	28	30	35
Additional filtration	60 μm Mo			
Al HVL / mm	0.332	0.355	0.364	0.388
$(\mu/\rho)_{\text{air}}$ / cm^2 g^{-1}	1.79	1.70	1.67	1.60
Reference distance / mm	500			
$\dot{K}_{\text{BIPM}}$ / mGy s^{-1}	1.00			

5.2 The BIPM standard and correction factors

The reference plane for the BIPM standard was positioned at 500 mm from the radiation source, with a reproducibility of 0.03 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm. The standard beam diameter in the reference plane is 100 mm for all radiation qualities. For this comparison, a tungsten collimator that halves the beam diameter was used to match the ENEA-INMRI field size.

During the calibration of the transfer chamber, measurements using the BIPM standard were made using positive polarity only. A correction factor of 1.000 5 was applied to correct for the known polarity effect in the standard. The leakage current for the BIPM standard, relative to the ionization current, was measured to be less than 1×10^{-4}.

The correction factors applied to the ionization current measured at each radiation quality using the BIPM standard, together with their associated uncertainties, are given in Table 5.

The correction factor k_a is evaluated for the reference distance of 500 mm using the measured mass attenuation coefficients $(\mu/\rho)_{\text{air}}$ given in Table 4. In practice, the values used for k_a take account of the temperature and pressure of the air in the standard at the time of the measurements. Ionization measurements (both for the standard and for transfer chambers) are also corrected for changes in air attenuation arising from variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point of the chamber was positioned in the reference plane at 500 mm with a reproducibility of 0.03 mm. The transfer chamber was aligned on the beam axis to an estimated uncertainty of 0.1 mm.

The leakage current was measured before and after each series of ionization current measurements and a correction made using the mean value. The leakage current, relative to the ionization current of around 200 pA, was less than 1 part in 10^4.

The standard uncertainty of the mean of a series of seven measurements, each with integration time 30 s, was less than 2 parts in 10^4.

Table 5. Correction factors for the BIPM FAC-L-01 standard

Radiation quality	W/Mo-23	W/Mo-28	W/Mo-30	W/Mo-35	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_{a}[a]	1.0218	1.0208	1.0203	1.0195	0.0002	0.0001
Scattered radiation k_{sc}	0.9974	0.9974	0.9974	0.9974	–	0.0003
Fluorescence k_{fl}	0.9972	0.9972	0.9972	0.9973	–	0.0005
Electron loss k_{e}	1.0000	1.0000	1.0000	1.0000	–	0.0001
Saturation k_{s}	1.0006	1.0006	1.0006	1.0006	0.0001	0.0001
Polarity k_{pol}	1.0005	1.0005	1.0005	1.0005	0.0001	–
Wall transmission k_{p}	1.0000	1.0000	1.0000	1.0000	0.0001	–
Field distortion k_{d}	1.0000	1.0000	1.0000	1.0000	–	0.0007
Diaphragm correction k_{dia}	0.9995	0.9995	0.9995	0.9995	–	0.0003
Humidity k_{h}	0.9980	0.9980	0.9980	0.9980	–	0.0003
$1 - g_{\mathrm{air}}$	1.0000	1.0000	1.0000	1.0000	–	0.0001

[a] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
$u_{i\mathrm{A}}$ 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

6. Calibration at the ENEA-INMRI

6.1 The ENEA-INMRI irradiation facility and reference radiation qualities

The mammography x-ray facility at the ENEA-INMRI is comprised of a constant-potential generator and a W-anode tube with an inherent filtration of 1.0 mm beryllium. The x-ray output is monitored continuously by means of a free-air monitor chamber.

The characteristics of the ENEA-INMRI realization of the mammography comparison qualities are given in Table 6.

Two calibrated NTC type thermometers were used to measure the air temperature, one positioned inside the standard chamber (or close to the transfer chamber during calibration) and the second close to the free-air monitor chamber. Air pressure was measured using a calibrated barometer positioned at the height of the beam axis. The relative humidity was in the range from 45 % to 55 %. No humidity correction has been applied to the transfer chamber current measurements.

Table 6. Characteristics of the ENEA-INMRI reference radiation qualities

Radiation quality	W/Mo-23	W/Mo-28	W/Mo-30	W/Mo-35
Generating potential / kV	23	28	30	35
Additional filtration	60 µm Mo			
Al HVL / mm	0.33	0.35	0.36	0.38
$(\mu/\rho)_{air}$ [a] / $cm^2\ g^{-1}$	1.73	1.68	1.66	1.57
Reference distance / mm	500			
$\dot{K}_{ENEA}$ / $mGy\ s^{-1}$	1.0	2.8	3.8	4.1

[a] Air attenuation coefficient at 293.15 K and 101.325 kPa, measured for an air path length of 65.12 mm.

6.2 The ENEA-INMRI standard and correction factors

The reference plane for the ENEA-INMRI standard was positioned at 500 mm from the anode of the x-ray tube, with a reproducibility of 0.2 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.2 mm. The beam diameter in the reference plane is 50 mm for all radiation qualities.

The correction factors applied to the ionization current measured at each radiation quality using the ENEA-INMRI standard, together with their associated uncertainties, are given in Table 7.

Table 7. Correction factors for the ENEA-INMRI CAL02 standard

Radiation quality	W/Mo-23	W/Mo-28	W/Mo-30	W/Mo-35	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.0137	1.0133	1.0131	1.0118	-	0.0020
Scattered radiation k_{sc}	0.9981	0.9981	0.9981	0.9981	-	0.0030
Fluorescence k_{fl}	0.9976	0.9977	0.9977	0.9977	-	0.0017
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	-	0.0010
Saturation k_s	1.0007	1.0008	1.0009	1.0010	-	0.0010
Polarity k_{pol}	0.9999	0.9999	0.9999	0.9999	0.0004	0.0003
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000		0.0010
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0020
Diaphragm correction k_{dia}	1.0000	1.0000	1.0000	1.0000	-	0.0006
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0010
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	-	0.0001

[a] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.

The correction factor k_a is evaluated using the measured mass attenuation coefficients $(\mu/\rho)_{air}$ given in Table 6. The values used for k_a take account of the temperature and pressure of the air in the standard at the time of the measurements. Ionization measurements (standard and transfer chambers) are also corrected for variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

6.3 Transfer chamber positioning and calibration at the ENEA-INMRI

The reference point of the transfer chamber was positioned at the reference distance with a reproducibility of 0.3 mm. Alignment on the beam axis was to an estimated uncertainty of 0.5 mm.

For each radiation quality, two sets of measurements were done using the primary standard and in between, one set of measurements using the transfer chamber. Each set consists of five measurements with an integration time of 100 s. The relative standard uncertainty of each set was less than 1 part in 10^3. The leakage current was measured before and after each series of ionization current measurements and a correction made using the mean value. The relative leakage current was less than 5 parts in 10^5.

The chamber was calibrated two times for each radiation quality before the measurements at the BIPM and two times following the BIPM measurements. The stated relative standard uncertainty for the reproducibility of the calibrations at the ENEA-INMRI is 2.3 parts in 10^3.

7. Additional considerations for transfer chamber calibrations

7.1 Ion recombination, polarity, field size and radial non-uniformity

The ENEA applies a correction for ion recombination calculated for each radiation quality as

$$k_{s,tr} = 1 + k_{init} + k_{vol} \times \mathrm{I} \tag{4}$$

where k_{init} is the initial recombination (k_{init} = 0.00196) and

k_{vol} is the volume recombination ($k_{vol} = 6.68 \times 10^5\ \mathrm{A}^{-1}$)

A relative standard uncertainty of 5 parts in 10^4 is included in Table 12 to account for this effect. As the ENEA-INMRI kerma rates are different for each quality and also different at the two laboratories (see Tables 4 and 6), the BIPM results have been corrected by k_s using the ENEA-INMRI determination. The correction applied to the current measured at the BIPM is 1.0021.

The transfer chamber was used with the same polarity at each laboratory and so no corrections are applied for polarity effects in the transfer chamber.

No correction is applied for field size as the BIPM field diameter was reduced to 50 mm to match the ENEA-INMRI field size.

No correction $k_{rn,tr}$ is applied at either laboratory for the radial non-uniformity of the radiation field as this effect is likely to cancel to some extent at the two laboratories. A relative standard uncertainty of 5×10^{-4} is introduced for this effect.

7.2 Radiation quality correction factors k_Q

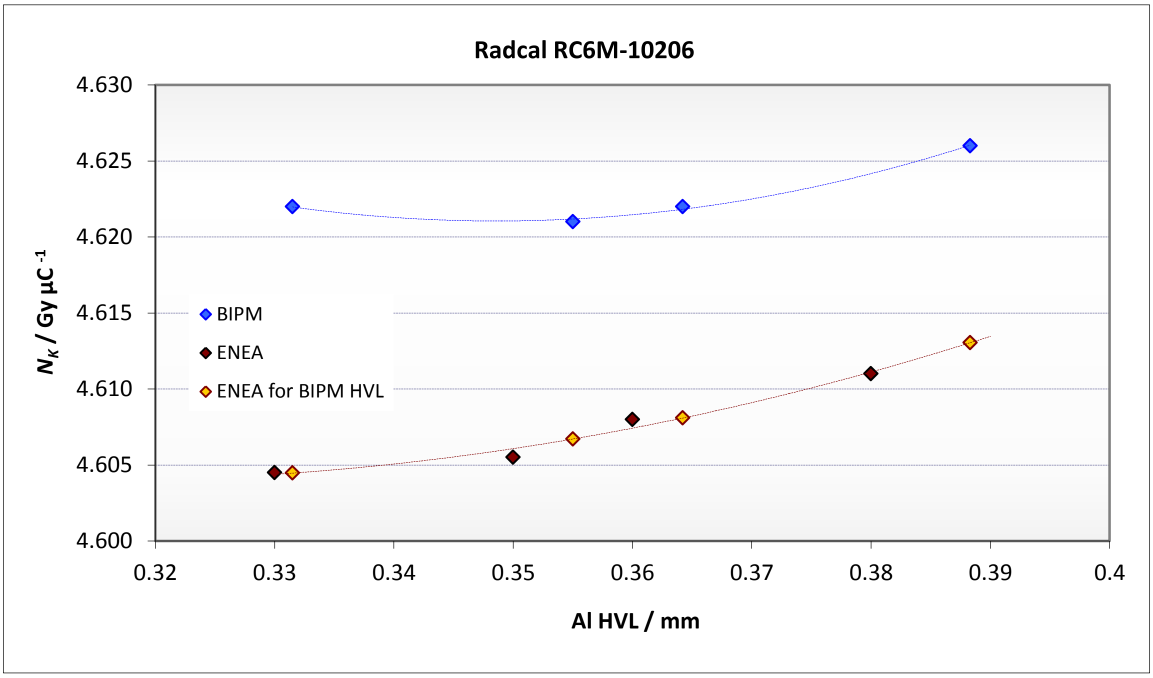
As noted in Section 4.1, differences in radiation qualities must be taken into account to evaluate a comparison result. Tables 4 and 6 show slight differences in the HVL at the BIPM and the ENEA-INMRI. To derive a comparison result for the BIPM HVL values, a quadratic fit was made to the ENEA-INMRI data set, as shown in Figure 1. From the fit, a set of k_Q values was derived to correct each ENEA-INMRI calibration coefficients into one that applies at the 'equivalent' BIPM quality.

The comparison result is then evaluated as

$$R_{K,\mathrm{ENEA}} = \frac{N_{K,\mathrm{ENEA}}\, k_Q}{N_{K,\mathrm{BIPM}}} \tag{5}$$

An additional uncertainty of 2 parts in 10^4 is included in Table 12 for this fitting procedure.

Figure 1. Calibration coefficients determined at the ENEA-INMRI and the BIPM



8. Comparison results

The transfer chamber was calibrated at the ENEA-INMRI before and after the BIPM measurements. The ENEA-INMRI and BIPM results are given in Table 8.

Table 8. Calibration coefficients for the transfer chamber

Radiation quality	W/Mo-23	W/Mo-28	W/Mo-30	W/Mo-35
$N_{K,\mathrm{ENEA\text{-}INMRI}}$ (pre-BIPM) / Gy µC^{-1}	4.605	4.604	4.605	4.608
$N_{K,\mathrm{ENEA\text{-}INMRI}}$ (post-BIPM) / Gy µC^{-1}	4.604	4.607	4.611	4.614
s_{tr} (relative)	0.0002	0.0005	0.0009	0.0009
s_{mean}	0.0007			
$N_{K,\mathrm{ENEA\text{-}INMRI}} \times k_Q$ / Gy µC^{-1}	4.605	4.606	4.609	4.613
$N_{K,\mathrm{BIPM}}$ [a] / Gy µC^{-1}	4.622	4.621	4.622	4.626

[a] To be consistent with the ENEA results, the BIPM calibration coefficients N_K have been corrected for ion recombination using $k_{\mathrm{s,tr}}$ = 1.0021

The values $N_{K,\mathrm{ENEA\text{-}INMRI}}$ measured before and after the measurements at the BIPM give rise to the mean value for s_{mean} in Table 8 of 7×10^{-4}. Nevertheless, based on the typical reproducibility at the ENEA-INMR, the stated reproducibility of their calibration coefficients is 2.3×10^{-3}. This latter value is included in Table 11 with no additional component in Table 12.

The ratios $N_{K,\text{ENEA-INMRI}}$ / $N_{K,\text{BIPM}}$ for the transfer chamber are given in Table 9. The final results $R_{K,\text{ENEA-INMRI}}$ include the correction factors k_Q according to equation (5).

Table 9. Comparison results

Radiation quality	W/Mo-23	W/Mo-28	W/Mo-30	W/Mo-35
$R_{K,\text{ENEA-INMRI}}$	0.9962	0.9968	0.9971	0.9972

9. Uncertainties

The uncertainties associated with the primary standards are listed in Table 10 and those for the transfer chamber calibrations in Table 11. The combined standard uncertainty u_c for the comparison results $R_{K,\text{ENEA-INMRI}}$ is presented in Table 12.

Table 10. Uncertainties associated with the standards at each laboratory

Standard	BIPM L-01		ENEA-INMRI	
Relative standard uncertainty	$u_{i\text{A}}$	$u_{i\text{B}}$	$u_{i\text{A}}$	$u_{i\text{B}}$
Ionization current	0.0002	0.0002	0.0005	0.0016
Volume	0.0003	0.0005	-	0.0005
Positioning	0.0001	0.0001	-	0.0008
Correction factors (excl. k_h)	0.0003	0.0010	-	0.0020
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}$	0.0005	0.0019	0.0005	0.0031

Table 11. Uncertainties associated with the calibration of the transfer chambers

Institute	BIPM		ENEA-INMRI	
Relative standard uncertainty	$u_{i\text{A}}$	$u_{i\text{B}}$	$u_{i\text{A}}$	$u_{i\text{B}}$
$\dot{K}$	0.0005	0.0019	0.0005	0.0031
Positioning of transfer chamber	0.0001	-	-	0.0010
I_tr	0.0002	0.0002	0.0010	0.0026
Reproducibility	0.0005	-	0.0023	-
N_K	0.0007	0.0019	0.0026	0.0042

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{ENEA\text{-}INMRI}} / N_{K,\mathrm{BIPM}}$	0.0027	0.0039[a]
Ion recombination $k_{\mathrm{s,tr}}$	-	0.0005
Radial non-uniformity $k_{\mathrm{rn,tr}}$	-	0.0005
Fitting procedure k_Q	-	0.0002
$R_{K,\mathrm{ENEA\text{-}INMRI}}$	0.0027	0.0040
	$u_{\mathrm{c}} = 0.0048$	

[a] Takes account of correlation in type B uncertainties.

The combined standard uncertainty u_{c} of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction. In the analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence described by Burns (2006), correlation in the values for the correction factors k_{e}, k_{sc} and k_{fl} is taken into account if the NMI has used values derived from Monte Carlo calculations, as is the case for the ENEA-INMRI standard.

10. Discussion

The comparison results presented in Table 9 show agreement between the ENEA-INMRI and BIPM standards at the level of around 3.5 parts in 10^3 with a combined standard uncertainty of 4.8 parts in 10^3.

This comparison was conducted using one transfer chamber rather than by direct comparison of the primary standards. While the use of transfer chambers introduces more uncertainty in the comparison results, the results obtained are more directly related to the disseminated quantity.

The ENEA-INMRI participated in 2011 in the BIPM.RI(I)-K2 comparison using the primary standards, being the same standards used for the mammography beams for both the ENEA-INMRI and the BIPM (Burns *et al* 2011). The direct comparison result for the quality 25 kV, W/Al beam, the closest in HVL to the mammography W/Mo beams, was 0.9976 (28); this result is in agreement, within the uncertainties, with the results presented in Table 9.

11. Degrees of Equivalence

The analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence is described by Burns (2003) and a similar analysis is adopted for comparisons in mammography x-ray beams. Following a decision of the CCRI, the BIPM determination of the air-kerma rate is taken as the key comparison reference value, for each of the CCRI radiation qualities. It follows that for each laboratory i having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ and its expanded uncertainty $U_i = 2\, u_i$. The results for D_i and U_i expressed in mGy/Gy, are shown in Table 13.

Table 13. Degrees of equivalence

	Mo/Mo-25		Mo/Mo-28		Mo/Mo-30		Mo/Mo-35	
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
	/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)	
NMIJ	**-1.6**	7.4	**-1.2**	7.4	**-1.4**	7.4	**-1.2**	7.4
PTB	**-0.9**	7.4	**-0.6**	7.4	**-0.9**	7.4	**-0.5**	7.4
NIST	**-2.6**	6.4	**-3.2**	6.4	**-3.4**	6.4	**-3.8**	6.4
VNIIM	**-3.7**	4.8	**-3.0**	4.8	**-2.7**	4.8	**-2.8**	4.8
VSL	**-5.6**	11.4	**-4.6**	11.4	**-5.3**	11.4	**-4.7**	11.4

	W/Mo-23		W/Mo-28		W/Mo-30		W/Mo-50	
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
	/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)	
NRC	**0.9**	6.0	**–**	**–**	**1.5**	1.0	**6.0**	6.0
	W/Mo-23		W/Mo-28		W/Mo-30		W/Mo-35	
ENEA-INMRI	**-3.8**	9.6	**-3.2**	9.6	**-2.9**	9.6	**-2.8**	9.6

Note that the data presented in the table, while correct at the time of publication of the present report, will become out of date when a laboratory makes a new comparison with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database.

When required, the degree of equivalence between two laboratories i and j can be evaluated as the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\,u_{ij}$, both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j (Burns 2003).

12. Conclusion

The key comparison BIPM.RI(I)-K7 for the determination of air kerma in mammography x-ray beams shows the standards of the ENEA-INMRI and the BIPM to be in agreement within the uncertainty of 4.9 parts in 10^3.

Degrees of equivalence, including those for the ENEA-INMRI, are presented for entry in the BIPM key comparison database. The formal results under the CIPM MRA are those available in the BIPM key comparison database.

References

Allisy P J, Burns D T, and Kessler C 2011 Measuring conditions and uncertainties for the comparison and calibration of national dosimetric standards at the BIPM *Rapport BIPM-*2011/04

Boutillon M, Henry W H and Lamperti P J 1969 Comparison of exposure standards in the 10-50 kV x-ray region *Metrologia* **5** 1-11

Burns D T and Kessler C 2009 Diaphragm correction factors for free-air chamber standards for air-kerma in x-rays, 2009, *Phys. Med. Biol.* **54**, 2737–2745.

Burns D T 2003 Degrees of equivalence for the key comparison BIPM.RI(I)-K2 between national primary standards for low-energy x-rays *Metrologia **40** Technical Supplement 06031*

Burns D T, Kessler C, Roger P, Toni M P, Pinto M, Bovi M, Cappadozzi G and Silvestri C 2011 Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the ENEA-INMRI, Italy and the BIPM in low-energy x-rays *Metrologia 48 Technical Supplement 06010*

Kessler C 2006 Establishment of simulated mammography radiation qualities at the BIPM *Rapport BIPM*-2006/08