Key comparison BIPM.RI(I)-K7 of the air-kerma standards of the NIST, USA 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 NIST and the BIPM in mammography x-ray beams. The results show the standards to be in agreement at the level of the combined standard uncertainty of 3.2 parts in 10^3. The results are analysed and presented in terms of degrees of equivalence for entry in the BIPM key comparison database.

1. Introduction

An indirect comparison has been made between the air-kerma standards of the National Institute of Standards and Technology (NIST), USA and the Bureau International des Poids et Mesures (BIPM) in the mammography x-ray range from 25 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 January 2010 using the reference conditions described in [1].

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, the correction for air density involves a temperature correction T / T_0, a pressure correction P_0 / P and a humidity correction $k_{\text{h}} = 0.9980$. 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.

3. Details of the standards

The BIPM free-air chamber standard for air kerma, described in [2], is of the conventional parallel-plate design in which V is defined by the diameter of the chamber aperture and the length of the collecting region. The NIST standard for mammography has a telescopic cylindrical geometry in which V is defined by the aperture diameter and the difference between the extended and collapsed chamber lengths. Details of the NIST standard are given in [3]. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

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.

Table 2. Main characteristics of the standards

Standard	BIPM L-02	NIST Attix
Aperture diameter / mm	9.998	5.011
Air path length / mm	100.0	212.7
Collecting length / mm	15.537	variable
Electrode separation / mm	70	87 [a]
Collector width / mm	70	1.6 [b]
Measuring volume / mm^3	1219.8	variable
Polarizing voltage / V	1500	2500

[a] The inner diameter of the cylindrical chamber.
[b] The diameter of the collector rod.

4. The transfer instruments

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

$$N_K = \frac{\dot{K}}{I_{tr}} \tag{2}$$

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 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. 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 of type Radcal RC6M, belonging to the NIST, was used as the transfer instrument for the comparison. The main characteristics are given in Table 3. The reference plane for the Radcal chamber was taken to be defined by the red line around the chamber casing and the reference point in this plane was taken to be on the axis defined by the entrance window.

Table 3. Main characteristics of the transfer chamber

Chamber type	Radcal RC6M
Serial number	10078
Window material	metalized polyester
Window thickness / mg cm^{-2}	0.7
Collector diameter / mm	30
Cavity height / mm	9
Nominal volume / cm^3	6
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 molybdenum-anode x-ray tube with an inherent filtration of 0.8 mm beryllium. A molybdenum filter of thickness 0.030 mm is added for all radiation qualities. A voltage divider is used to measure the generating potential, which is stabilized using an additional feedback system of 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-02 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 25 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	Mo-25	Mo-28	Mo-30	Mo-35
Generating potential / kV	25	28	30	35
Additional filtration	30 μm Mo			
Al HVL / mm	0.277	0.310	0.329	0.365
$(\mu/\rho)_{air}$ / cm^2 g^{-1}	2.20	1.99	1.91	1.74
$\dot{K}_{BIPM}$ / mGy s^{-1}	2.00			

5.2 The BIPM standard and correction factors

The reference plane for the BIPM standard was positioned at 600 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 beam diameter in the reference plane is 100 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the BIPM standard were made using positive polarity only as the polarity effect in the standard is less than 1 part in 10^4. Nevertheless, the polarity effect was confirmed each day of the comparison for one radiation quality. 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.

Table 5. Correction factors for the BIPM FAC-L-02 standard

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.0269	1.0243	1.0233	1.0212	0.0002	0.0001
Scattered radiation k_{sc}	0.9977	0.9977	0.9978	0.9978	–	0.0003
Fluorescence k_{fl}	0.9975	0.9976	0.9976	0.9977	–	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	–	0.0001
Saturation k_s	1.0015	1.0015	1.0015	1.0015	0.0001	0.0001
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	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}	0.9996	0.9995	0.9995	0.9995	–	0.0003
Humidity k_h	0.9980	0.9980	0.9980	0.9980	–	0.0003
$1 - g_{air}$	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.

u_{iA} represents the relative standard uncertainty estimated by statistical methods, type A

u_{iB} represents the relative standard uncertainty estimated by other means, type B

The correction factor k_a is evaluated for the reference distance of 600 mm using the measured mass attenuation coefficients $(\mu/\rho)_{air}$ 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 for the Radcal transfer chamber was positioned in the reference plane with a reproducibility of 0.03 mm. The 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 relative leakage current for the transfer chamber was always less than 1×10^{-4}.

The chamber was calibrated three times, being repositioned for the third calibration. A relative standard uncertainty component of 1×10^{-3} is included to account for the reproducibility of the calibrations at the BIPM.

6. Calibration at the NIST

6.1 The NIST irradiation facility and reference radiation qualities

The mammography x-ray facility at the NIST is comprised of a constant-potential generator and a Mo-anode tube with an inherent filtration of 1 mm beryllium. The materials used for the filtration and for the measurement of HVL were at least 99.99 % pure with thicknesses known with an uncertainty of 0.01 mm. The high voltage was verified through the use of a custom-designed invasive voltage divider.

The characteristics of the NIST realization of the mammography comparison qualities are given in Table 6.

Table 6. Characteristics of the NIST reference radiation qualities [a]

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35
Generating potential / kV	25	28	30	35
Additional filtration	32 μm Mo			
Al HVL[a] / mm	0.299	0.335	0.358	0.395
$(\mu/\rho)_{air}$ / cm^2 g^{-1}	2.31	2.20	2.08	1.92
$\dot{K}_{NIST}$ / mGy s^{-1}	1.57	2.25	2.79	1.96

[a] Values are given for a distance of 650 mm, rather than the usual NIST reference distance of 1000 mm.

During all calibrations the laboratory temperature was maintained between 20 °C and 24 °C and was stable to 0.2 °C for a typical measurement series of 10 min. A thermistor measures the temperature of the air inside the shielding box surrounding the free-air chamber. Air pressure is measured by means of a calibrated barometer positioned in the control room. Relative humidity in the NIST laboratory is monitored and was typically 30 % during the comparison measurements. No correction for humidity was applied to the current measured using the transfer chamber.

6.2 The NIST standard and correction factors

The normal reference distance at the NIST is 1000 mm. However, for the present comparison, to match the BIPM reference distance, the reference plane for the NIST standard was positioned at 650 mm from the radiation source, with a reproducibility of 0.01 mm. Alignment of the standard on the beam axis was measured to an accuracy of around 0.1 mm and this position was reproducible to better than 0.01 mm, as observed by an alignment telescope. The beam diameter in the reference plane is 60 mm for all radiation qualities, significantly smaller than the BIPM beam diameter of 100 mm, and is a consequence of the change in reference distance.

No correction factor k_{pol} was applied to the NIST standard as the measurements were made using both polarities. The relative leakage current was measured to be 1×10^{-4}.

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

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. The air-attenuation correction is measured directly by the Attix chamber at the reference distance of 650 mm.

Table 7. Correction factors for the NIST Attix standard

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.0610	1.0580	1.0548	1.0504	-	0.0001
Scattered radiation k_{sc}	0.9950	0.9950	0.9951	0.9952	-	0.0007
Electron loss k_e	1.000	1.000	1.000	1.000	-	0.0005
Saturation k_s	1.000	1.000	1.000	1.000	0.0004	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	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.

6.3 Transfer chamber positioning and calibration at the NIST

The reference point for the chamber was positioned in the reference plane with a reproducibility of 0.01 mm. Alignment on the beam axis was 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 relative leakage current for the Radcal chamber was typically 1×10^{-4}.

The chamber was calibrated a minimum of 30 times for each radiation quality before the measurements at the BIPM and a minimum of 10 times following the BIPM measurements. The relative standard uncertainty of the distribution is 1.7×10^{-3}; a relative standard uncertainty of the mean of 3×10^{-4} is included to account for the long-term stability of the calibrations at the NIST.

7. Additional considerations for transfer chamber calibrations

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

No corrections $k_{s,tr}$ are applied for ion recombination and a relative standard uncertainty of 5×10^{-4} is introduced to account for the difference in the kerma rates at the two laboratories. The transfer chamber was used with the same polarity at each institute and so no corrections are applied for polarity effects in the transfer chamber.

No correction $k_{rn,tr}$ is applied at either laboratory for the radial non-uniformity of the radiation field. For a chamber with collector radius 15 mm, the correction factor for the BIPM reference field is around 5×10^{-4} and this effect is likely to cancel to some extent at the two laboratories. A relative standard uncertainty of 2×10^{-4} is introduced for this effect.

The radiation field diameter is significantly different at the two laboratories (100 mm at the BIPM and 60 mm for the non-standard conditions used at the NIST). While the effect of this on calibration coefficients can be significant for some chamber types, particularly at higher energies, the Radcal is known to be relatively insensitive to field size in the mammography range and an uncertainty component of 1 part in 10^3 is included for this effect.

7.2 HVL considerations

The mean calibration coefficients determined at the NIST and at the BIPM, normalized to the BIPM calibration coefficient for the CCRI 25 kV quality, are plotted in Figure 1 as a function of the corresponding HVL. Note that the NIST Mo-23 quality was measured subsequent to and was not part of the original comparison.

Figure1. Normalized calibration coefficients N_K for the Radcal RC6M-10078

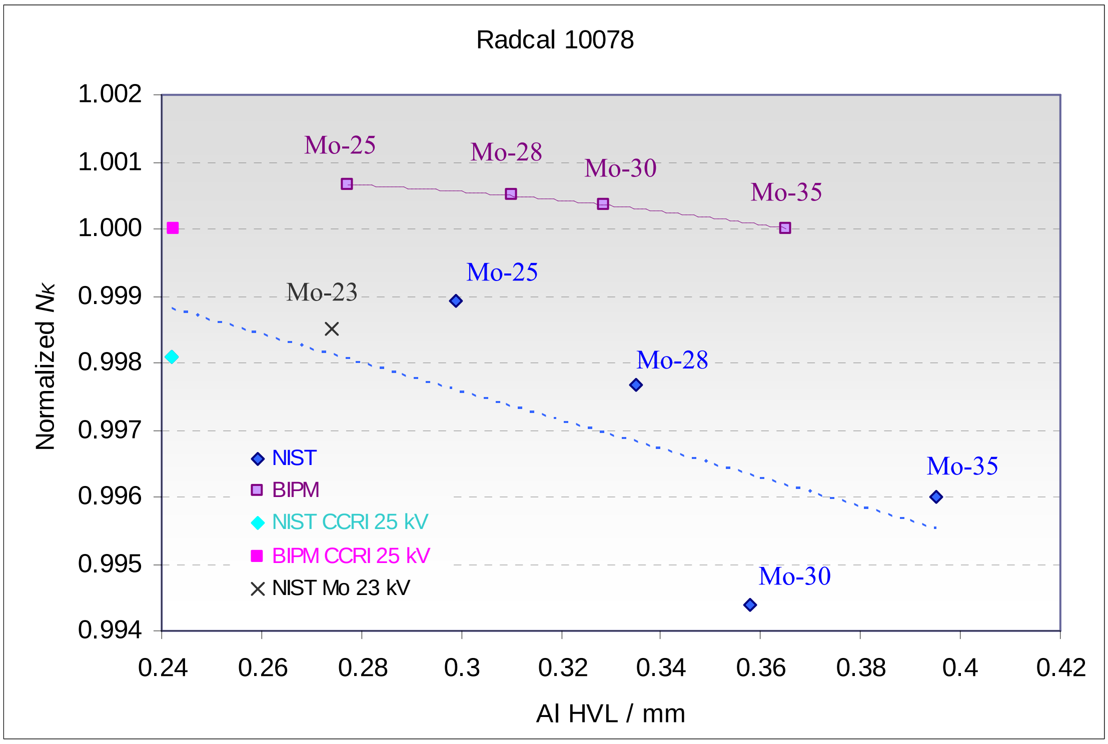

Figure 1. Normalized results for the transfer chamber calibration coefficients at the NIST and the BIPM. The dashed blue line through the NIST data represents a linear fit to the NIST data points, including the CCRI 25 kV quality but excluding the Mo-23 quality (see explanation in text).

It can be seen from the BIPM data that the chamber exhibits a smooth and relatively flat energy response, the total variation being less than 7 parts in 10^4 over the energy range considered. In contrast, the NIST results show significant scatter and a total variation in the chamber response of 4.6 parts in 10^3.

From Tables 4 and 6 (and Figure 1) it is evident that the radiation qualities at the BIPM and at the NIST are not well matched in terms of HVL, despite the use of the same calibrated generating potentials and similar molybdenum filters. In combination with the scatter of the NIST data, this presents a difficulty in deriving a comparison result for each of the BIPM radiation qualities.

To this end, a linear fit was made to the NIST data; to avoid the need for extrapolation to the BIPM Mo-25 HVL, the calibration coefficient for the CCRI 25 kV quality at the NIST was included in the linear fit (the NIST Mo-23 calibration point shown in Figure 1 is not included in the fit for the reason outlined below). From this fit, a set of values $N_{K,\mathrm{NIST}}$(BIPM HVL) was derived, leading to a set of comparison results

$$R_{K,\mathrm{NIST}} = \frac{N_{K,\mathrm{NIST}}(\mathrm{BIPM\ HVL})}{N_{K,\mathrm{BIPM}}} . \tag{3}$$

The uncertainty arising from the fitting procedure, which not only corrects for HVL differences but effectively smoothes the NIST data, is taken as the r.m.s. deviation of the measured values $N_{K,\mathrm{NIST}}$ from the fitted line. This is evaluated as 1.5 parts in 10^3 and is included in Table 12.

During subsequent discussions of the comparison results, the NIST measured the calibration coefficient for the Mo-23 quality to check the chamber's energy response and the result is included in Figure 1. However, due to the possibility of chamber drift, this new value was not taken into account in the analysis of the results, but it nevertheless serves to justify the method used to derive the comparison results.

8. Comparison results

The transfer chamber was calibrated at the NIST before and after the BIPM measurements. The calibration coefficients determined at the NIST are given in Table 8.

Table 8. Calibration coefficients measured at the NIST

Chamber	Date	$N_{K,\mathrm{NIST}}$ for the NIST HVLs	NIST radiation quality – Al HVL / mm			
			Mo-25 0.299	Mo-28 0.335	Mo-30 0.358	Mo-35 0.395
Radcal 10078	2009-11 to 2010-01	$N_{K,\mathrm{NIST}}$ / Gy μC^{-1}	4.7639	4.7579	4.7426	4.7494
	2010-06 to 2010-09	$N_{K,\mathrm{NIST}}$ / Gy μC^{-1}	4.7639	4.7579	4.7419	4.7506
Mean N_K			4.7639	4.7579	4.7423	4.7500

As described in section 7.2, the NIST calibration coefficients were fitted with a linear regression to calculate N_K values corresponding to the BIPM HVLs. The results from the linear fit are presented in Table 9, together with the values $N_{K,\mathrm{BIPM}}$ measured at the BIPM and the final comparison results $R_{K,\mathrm{NIST}}$.

Table 9. Calibration coefficients for the BIPM HVLs

Chamber	N_K for the BIPM HVLs	BIPM radiation quality – Al HVL / mm			
		Mo-25 0.277	Mo-28 0.310	Mo-30 0.329	Mo-35 0.365
Radcal 10078	fitted $N_{K,\mathrm{NIST}}$(BIPM HVL) / Gy µC^{-1}	4.7597	4.7564	4.7545	4.7508
	$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	4.7722	4.7715	4.7707	4.7691
$R_{K,\mathrm{NIST}} = N_{K,\mathrm{NIST}}$(BIPM HVL) / $N_{K,\mathrm{BIPM}}$		0.9974	0.9968	0.9966	0.9962

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 uncertainty for the comparison results $R_{K,\mathrm{NIST}}$ is presented in Table 12.

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. As the NIST correction factors k_{sc} and k_e for the standard were not calculated using Monte Carlo methods, no correlation is assumed for these factors.

Table 10. Uncertainties associated with the standards

Standard	BIPM		NIST	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0013	0.0006
Volume	0.0003	0.0005	0.0001	0.0007
Positioning	0.0001	0.0001	-	0.0001
Correction factors (excl. k_h)	0.0003	0.0010	0.0004	0.0009
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}$	0.0005	0.0019	0.0014	0.0020

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

Institute	BIPM		NIST	
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	0.0014	0.0020
Positioning of transfer chamber	0.0001	-	-	0.0001
I_{tr}	0.0003	0.0002	0.0005	0.0006
Reproducibility / stability	0.0010	-	0.0003	-
N_K	0.0012	0.0019	0.0015	0.0021

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\text{A}}$	$u_{i\text{B}}$
$N_{K,\text{NIST}}$ / $N_{K,\text{BIPM}}$	0.0019	0.0018[a]
$k_{\text{rn,tr}}$	-	0.0002
$k_{\text{s,tr}}$	-	0.0005
Field size	-	0.0010
Fitting procedure	-	0.0015
$R_{K,\text{NIST}}$	0.0025	0.0026
	u_c = 0.0032	

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

10. Discussion

In the comparison results presented in Table 9, agreement at the level of 3 to 4 parts in 10^3 is observed, which is consistent with the combined relative standard uncertainty for the comparison of 3.2 parts in 10^3. A trend of around 1 part in 10^3 is seen in the results at different radiation qualities, although given the uncertainty associated with the fitting procedure adopted for the NIST calibration coefficients no significance can be attributed to this trend.

For a given generating potential, differences in the Al HVL values of between 22 µm and 30 µm are observed for the two laboratories. The NIST uses a Mo filter 32 µm thick while at the BIPM the thickness is 30 µm. Simulations of both sets of radiation qualities using the IPEM software [4] show that the different Mo filter thicknesses can explain around 9 µm of the observed difference in the HVL values.

Another possible source of HVL differences is the calibration of the generating potentials. It can be seen from Figure 1 that a change in generating potential of 2 kV to 4 kV would result in better agreement between the NIST and BIPM HVLs. However, such a voltage offset is significantly larger than the calibration uncertainty of the voltage measurement at each laboratory. Furthermore, the systematic progression from 2 kV to 4 kV with increasing HVL is unlikely to be due to a voltage calibration error.

This comparison was conducted using a 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.

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 in [5] 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. 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 the NIST makes a new comparison with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database.

Table 13. Degrees of equivalence

	Mo-25		Mo-28		Mo-30		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)	
NIST	-2.6	6.4	-3.2	6.4	-3.4	6.4	-3.8	6.4

The degree of equivalence of laboratory i with respect to each laboratory j that has taken part in a BIPM comparison is the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\, u_{ij}$. Although the BIPM no longer calculates pair-wise degrees of equivalence, following the advice of the CCRI in June 2011, now that several NMIs have taken part in a BIPM mammography comparison the results of the comparisons could be analysed as follows. The combined standard uncertainty u_{ij} is mainly the combined uncertainty of the air-kerma rate determinations for laboratories i and j. In evaluating each u_{ij}, correlation between the standards should be removed, notably that arising from k_{sc} and k_{fl}. As described in [5], if correction factors based on Monte Carlo calculations are used by both laboratories, or by neither, then half the uncertainty value should be taken for each factor. Note that the uncertainty of the BIPM determination of air-kerma rate does not enter in u_{ij}, although the uncertainty arising from the comparison procedure is included.

12. Conclusion

A key comparison BIPM.RI(I)-K7 for the determination of air-kerma in mammography x-rays, carried out indirectly using one transfer chamber, shows the standards of the NIST, USA and the BIPM to be in agreement at the level of the standard uncertainty for the comparison of 3.2 parts in 10^3. Degrees of equivalence are presented for entry in the BIPM key comparison database.

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