Degrees of equivalence for the key comparison BIPM.RI(I)-K2 between national primary standards for low-energy x-rays

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Abstract Results are presented of comparisons of eleven national primary standards for air kerma with the BIPM primary standard over the range of x-radiation qualities from 10 kV to 50 kV. For each radiation quality, the results are analysed in terms of the degree of equivalence, D_i, of each national standard i with respect to the key comparison reference value. The degrees of equivalence, D_{ij}, between each pairing of national standards i and j are also evaluated. These data form the basis of the matrices and graphs of results entered in the BIPM key comparison database for comparison BIPM.RI(I)-K2.

1. Introduction

The present report is based upon that presented to Section I of the CCRI in May 2003. In that report, the results of eleven BIPM comparisons for low-energy x-rays were analysed and values proposed for the degrees of equivalence between the national primary standards that had taken part in these comparisons. The CCRI(I) showed support for the method of analysis and decided on a timescale for the validation of the data and their inclusion in the BIPM key comparison database.

Each data set was validated by the laboratory concerned with reference to the results published in the relevant comparison report. In addition, each laboratory confirmed that the standard presently being disseminated was correctly represented by the results presented to the CCRI(I), in particular that no changes had been made to correction factors, with the following two exceptions.

The NIST (USA) has recently changed several of their correction factors. Consequently, the NIST results presented to the CCRI(I) are no longer valid and have been updated for the present report. The changes to the NIST standard are documented in Appendix 1.

The METAS (Switzerland) noted a difference between the results presented to the CCRI(I) and those in the relevant comparison report. This resulted from two errors in the comparison report, the results presented to the CCRI(I) being correct since they were derived from the original comparison file held at the BIPM. This difference is documented in Appendix 2.

It should be noted that, following a decision of the CCRI(I) taken in 2001, the present report includes new values for the photon-scatter correction factor, k_{sc}, for the BIPM standard, as well as a new factor, k_{fl}, that corrects for the re-absorption of fluorescent photons in the free-air chamber. These changes are documented in [1].

2. BIPM key comparisons

Comparisons of national primary standards with the BIPM primary standard in low-energy x-rays are designated as key comparisons with reference BIPM.RI(I)-K2. Such comparisons have been conducted on an ongoing basis since 1966. As the standards are generally transportable, these comparisons are normally carried out directly at the BIPM at a series of reference radiation qualities. Two comparisons (with Poland and Russia) were carried out indirectly, each using a small free-air chamber as the transfer standard.

The results of comparisons are expressed in the form of the ratio, x_i, of the air-kerma rate determination of laboratory i to that of the BIPM, and the combined standard uncertainty u_i of this ratio, for each of the radiation qualities. The uncertainty u_i includes the uncertainties of the determinations of air-kerma rate by laboratory i and by the BIPM, taking into account correlations between the two standards. The most notable correlations are in the values used for the physical constants ρ_{air} and W_{air} / e, for the humidity correction k_h, and for the bremsstrahlung correction (1–g_{air}), which therefore do not enter in the calculation of u_i.

Account must also be taken of correlations in the values used for k_e and k_{sc}. The new values for the BIPM standard are derived from Monte Carlo calculations, as are those for the NIST, the PTB (Germany) and the OMH (Hungary). As in the report presented to and approved by the CCRI(I), this correlation is treated by taking half the stated standard uncertainties for the BIPM and for the laboratory (NIST, PTB or OMH). Note also that correlations in k_e and k_{sc} exist when evaluating the degrees of equivalence between pairs of NMIs (see Section 4).

All other uncertainty components are assumed to be uncorrelated, namely those arising from the free-air chamber volume determinations V_{std}, the ionization current measurements I_{std}, and the correction factors for air attenuation k_a, ion recombination k_s, electric field distortion k_d, aperture edge transmission k_l and chamber wall transmission k_p. A component z_{pos} is included to take account of the positioning uncertainty of the laboratory standard relative to the BIPM standard.

The comparison results x_i for each laboratory are given in Table 1. For a given laboratory, the combined standard uncertainty of the comparison u_i applies to all of the radiation qualities. Cells shaded in grey indicate that this radiation quality was not used during the relevant comparison. The uncertainty components giving rise to the u_i are presented in Table 2. These are taken from the appropriate reference cited in Table 1. For the GUM (Poland), the cited report [3] does not include an uncertainty budget and the values given in Table 2 are taken from the comparison file held at the BIPM. Two of the cited reports, [3] and [8], do not contain the detailed uncertainty budget for the BIPM standard. This is given in [14]. The final column of Table 2 is the combined relative standard uncertainty $u_{Lab\,i}$ for each standard, including the components ρ_{air}, W_{air} / e, k_h and (1–g_{air}) removed from the comparison uncertainty u_i due to correlations.

Table 1. Comparison results x_i at each of the radiation qualities. For each laboratory i, the standard uncertainty of the comparison u_i applies to all of the radiation qualities.

Lab i	Date of comparison	Report reference	x_i					u_i
			10 kV	30 kV	25 kV	50 kVb [a]	50 kVa [a]	
NRC	1966	[2]	1.0037	1.0016			1.0002	0.0033
GUM	1994	[3]	0.9993	0.9986		0.9977	0.9984	0.0027
NMi	1996	[4]	1.0002	0.9997		0.9993	0.9970	0.0023
NPL	1997	[5]	1.0013	0.9993	1.0010		0.9984	0.0024
NIST	1998	[6,7][b]	0.9958	0.9944	0.9947	0.9939	0.9956	0.0026
METAS	1998	[8][c]	1.0024	1.0006	1.0009	0.9993	0.9992	0.0017
ENEA	1998	[9]	1.0002	0.9971	0.9971	0.9975	0.9973	0.0025
VNIIM	1998	[10]	0.9962		0.9963	0.9975	0.9990	0.0026
PTB	1999	[11]	1.0030	0.9965	0.9978	0.9978	0.9989	0.0025
BEV	2001	[12]	0.9990	0.9972	0.9984	0.9981	0.9981	0.0024
OMH	2001	[13]	1.0012	1.0000	1.0006	1.0007	1.0003	0.0020

a) By convention, the more penetrating 50 kVquality is referred to as 50 kVa and the less penetrating as 50 kVb.
b) See also Appendix 1.
c) See also Appendix 2.

Table 2. Components of the combined standard uncertainty $u_{\text{Lab}\,i}$ for each laboratory *i*, expressed in parts in 10^3. These values apply to all radiation qualities.

Lab *i*	Uncertainty component											Combined uncertainty
	V_{std}	I_{std}	z_{pos}	k_{a}	k_{sc}	k_{fl} [a]	k_{e}	k_{s}	k_{d} [b]	k_{l}	k_{p}	$u_{\text{Lab}\,i}$ [c]
BIPM	**0.6**	**0.4** [d]	**-**	**0.3**	**0.3**	**0.5**	**0.1**	**0.2**	**0.7**	**0.1**	**0.1**	**2.0**
NRC	2.0	0.3	0.2	0.2	1.0 [e]	-	0.0	0.2	2.0	0.0	0.0	3.4
GUM	0.6 [f]	0.5	0.3	1.5	1.5	-	0.1	0.3	0.5	0.1	0.1	2.8
NMi	1.0	0.8	0.2	0.3	0.7	-	1.0	0.1	0.8	0.0	0.0	2.5
NPL	1.5	0.4	0.2	0.3	1.2	-	0.1	0.3	0.3	0.1	0.1	2.6
NIST	0.4	0.5	0.3	0.3	0.7	0.5	1.0	0.4	2.0	0.4	0.1	3.0
METAS	0.2	0.3	0.2	0.3	1.0	-	0.1	0.4	0.2	0.1	0.1	2.0
ENEA	0.5	0.5	0.6	0.3	1.0	-	1.0	0.5	1.0	0.5	0.5	2.7
VNIIM	0.8	1.3	0.4	1.1	1.0	-	0.5	0.2	0.7	0.1	0.1	2.8
PTB	0.6	0.5	0.3	0.3	0.5		0.5	0.7	1.7	0.5	0.7 [g]	2.8
BEV	1.0	0.5	0.2	0.3	1.0	-	0.5	0.7	1.0	0.2	0.3	2.6
OMH	1.1	0.5	0.2	0.3	1.5	-	0.5	0.4	0.5	0.1	0.2	2.6

a) Only the BIPM applies k_{fl} explicitly, although the effect of fluorescence is included in the PTB value for k_{sc}.
b) This includes the uncertainty of the polarity correction, where applicable.
c) Includes 1.5 for W_{air}/e, 0.3 for k_{h}, 0.1 for ρ_{air} and 0.1 for $(1-g_{\text{air}})$; these cancel in the comparison uncertainty u_i.
d) Only the statistical component of I_{std} for the BIPM standard, taken to be 0.2, is used in evaluating U_{ij}.
e) This value was chosen to give agreement with reported uncertainty when correlations are taken into account.
f) This is a compromise value, the given values being 1.0 at 10 kV and 0.3 at other radiation qualities.
g) Comprises 0.5 for wall transmission k_{p} and 0.5 for guard strip attenuation k_{ap}.

3. Degrees of equivalence with respect to the reference value

The CCRI(I) took the decision at its meeting in 1999 to use the BIPM determination of air-kerma rate as the basis of the key comparison reference value, x_{R}. It follows that $x_{\text{R}} = 1$. For each laboratory *i* with a comparison result x_i determined with combined standard uncertainty u_i, the degree of equivalence D_i with respect to the reference value is therefore simply $x_i - 1$ with expanded uncertainty $U_i = 2\,u_i$. The results for the degrees of equivalence D_i and the expanded uncertainties U_i are presented in Figures 1 to 5 for the five radiation qualities.

4. Degrees of equivalence between pairs of laboratories

For any pair of laboratories *i* and *j*, the degree of equivalence D_{ij} is the difference $D_i - D_j$, which is also the difference $x_i - x_j$ in the comparison results. The expanded uncertainty is $U_{ij} = 2\,u_{ij}$, where the combined standard uncertainty u_{ij} is principally the combined uncertainty of the air-kerma rate determinations for the laboratories *i* and *j*. In evaluating u_{ij} for each pairing, correlations between the standards are removed on the same basis as described above, notably regarding k_{e} and k_{sc}; if correction factors based on Monte Carlo calculations are used by both laboratories *i* and *j*, or by neither *i* nor *j*, then half the uncertainty value is taken for each. 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, that is, the statistical component (2×10^{-4} in relative value) for each of two sets of ionization current measurements using the BIPM standard.

The results for the degrees of equivalence D_{ij} and expanded uncertainties U_{ij} are given in Tables 3 to 7 for the five radiation qualities.

5. Summary

The results of eleven BIPM key comparisons for low-energy x-ray standards are summarized in Table 1, the component uncertainties being listed in Table 2. These data give rise to the degrees of equivalence presented in Tables 3 to 7 and in Figures 1 to 5. The format of Tables 3 to 7 and Figures 1 to 5 and the wording of the introductory text to each table are those agreed by the CCRI(I) for the entry of these data in the BIPM key comparison database.

The degrees of equivalence arising from future BIPM comparisons will be added to the database as soon as each comparison report is approved. For repeat comparisons with a given laboratory, the new values will replace the old.

Table 3. Degrees of equivalence and introductory text for the 10 kV radiation quality

Key comparison BIPM.RI(I)-K2

MEASURAND : Air-kerma rate relative to the BIPM evaluation
Radiation quality 10 kV

Key comparison reference value: the measurand is a ratio with reference value $x_R = 1$

The degree of equivalence of each laboratory i with respect to x_R is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty (k = 2), both dimensionless,
where $U_i = 2u_i$.

The degree of equivalence between two laboratories i and j is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty (k = 2), both dimensionless.
In evaluating $U_{ij} = 2\,u_{ij}$ for the table below, account is taken of correlations between u_i and u_j (see page 3 of the Summary Report).

Lab j ⇨

Lab i ⇩	D_i / 10^{-3}	U_i / 10^{-3}	NRC D_{ij} / 10^{-3}	NRC U_{ij} / 10^{-3}	GUM D_{ij} / 10^{-3}	GUM U_{ij} / 10^{-3}	NMi D_{ij} / 10^{-3}	NMi U_{ij} / 10^{-3}	NPL D_{ij} / 10^{-3}	NPL U_{ij} / 10^{-3}	NIST D_{ij} / 10^{-3}	NIST U_{ij} / 10^{-3}	METAS D_{ij} / 10^{-3}	METAS U_{ij} / 10^{-3}	ENEA D_{ij} / 10^{-3}	ENEA U_{ij} / 10^{-3}	VNIIM D_{ij} / 10^{-3}	VNIIM U_{ij} / 10^{-3}	PTB D_{ij} / 10^{-3}	PTB U_{ij} / 10^{-3}	BEV D_{ij} / 10^{-3}	BEV U_{ij} / 10^{-3}	OMH D_{ij} / 10^{-3}	OMH U_{ij} / 10^{-3}
NRC	3.7	6.5	-	-	4.4	7.0	3.5	6.7	2.4	6.8	7.9	8.0	1.3	6.1	3.5	6.9	7.5	7.2	0.7	7.7	4.7	6.9	2.5	7.4
GUM	-0.7	5.3	-4.4	7.0	-	-	-0.9	5.2	-2.0	5.3	3.5	7.0	-3.1	4.3	-0.9	5.3	3.1	5.8	-3.7	6.7	0.3	5.4	-1.9	6.4
NMi	0.2	4.7	-3.5	6.7	0.9	5.2	-	-	-1.1	4.9	4.4	6.5	-2.2	3.8	0.0	4.9	4.0	5.5	-2.8	6.1	1.2	5.0	-1.0	5.8
NPL	1.3	4.8	-2.4	6.8	2.0	5.3	1.1	4.9	-	-	5.5	6.6	-1.1	4.0	1.1	5.1	5.1	5.6	-1.7	6.2	2.3	5.1	0.1	5.9
NIST	-4.2	5.3	-7.9	8.0	-3.5	7.0	-4.4	6.5	-5.5	6.6	-	-	-6.6	5.7	-4.4	6.8	-0.4	7.0	-7.2	6.5	-3.2	6.6	-5.4	5.8
METAS	2.4	3.5	-1.3	6.1	3.1	4.3	2.2	3.8	1.1	4.0	6.6	5.7	-	-	2.2	4.0	6.2	4.6	-0.6	5.3	3.4	4.1	1.2	4.9
ENEA	0.2	5.0	-3.5	6.9	0.9	5.3	0.0	4.9	-1.1	5.1	4.4	6.8	-2.2	4.0	-	-	4.0	5.6	-2.8	6.4	1.2	5.1	-1.0	6.1
VNIIM	-3.8	5.3	-7.5	7.2	-3.1	5.8	-4.0	5.5	-5.1	5.6	0.4	7.0	-6.2	4.6	-4.0	5.6	-	-	-6.8	6.6	-2.8	5.6	-5.0	6.4
PTB	3.0	5.1	-0.7	7.7	3.7	6.7	2.8	6.1	1.7	6.2	7.2	6.5	0.6	5.3	2.8	6.4	6.8	6.6	-	-	4.0	6.2	1.8	5.6
BEV	-1.0	4.8	-4.7	6.9	-0.3	5.4	-1.2	5.0	-2.3	5.1	3.2	6.6	-3.4	4.1	-1.2	5.1	2.8	5.6	-4.0	6.2	-	-	-2.2	6.0
OMH	1.2	4.1	-2.5	7.4	1.9	6.4	1.0	5.8	-0.1	5.9	5.4	5.8	-1.2	4.9	1.0	6.1	5.0	6.4	-1.8	5.6	2.2	6.0	-	-

Table 4. Degrees of equivalence and introductory text for the 30 kV radiation quality

Key comparison BIPM.RI(I)-K2

MEASURAND : **Air-kerma rate relative to the BIPM evaluation**
Radiation quality 30 kV

Key comparison reference value: the measurand is a ratio with reference value $x_R = 1$

The degree of equivalence of each laboratory i with respect to x_R is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty (k = 2), both dimensionless,
where $U_i = 2u_i$.

The degree of equivalence between two laboratories i and j is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty (k = 2), both dimensionless.
In evaluating $U_{ij} = 2\,u_{ij}$ for the table below, account is taken of correlations between u_i and u_j (see page 3 of the Summary Report).

Lab j ⇨

Lab i ⇩			NRC		GUM		NMi		NPL		NIST		METAS		ENEA		PTB		BEV		OMH	
	D_i / 10^{-3}	U_i	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}
NRC	1.6	6.5	-	-	3.0	7.0	1.9	6.7	2.3	6.8	7.2	8.0	1.0	6.1	4.5	6.9	5.1	7.7	4.4	6.9	1.6	7.4
GUM	-1.4	5.3	-3.0	7.0	-	-	-1.1	5.2	-0.7	5.3	4.2	7.0	-2.0	4.3	1.5	5.3	2.1	6.7	1.4	5.4	-1.4	6.4
NMi	-0.3	4.7	-1.9	6.7	1.1	5.2	-	-	0.4	4.9	5.3	6.5	-0.9	3.8	2.6	4.9	3.2	6.1	2.5	5.0	-0.3	5.8
NPL	-0.7	4.8	-2.3	6.8	0.7	5.3	-0.4	4.9	-	-	4.9	6.6	-1.3	4.0	2.2	5.1	2.8	6.2	2.1	5.1	-0.7	5.9
NIST	-5.6	5.3	-7.2	8.0	-4.2	7.0	-5.3	6.5	-4.9	6.6	-	-	-6.2	5.7	-2.7	6.8	-2.1	6.5	-2.8	6.6	-5.6	5.8
METAS	0.6	3.5	-1.0	6.1	2.0	4.3	0.9	3.8	1.3	4.0	6.2	5.7	-	-	3.5	4.0	4.1	5.3	3.4	4.1	0.6	4.9
ENEA	-2.9	5.0	-4.5	6.9	-1.5	5.3	-2.6	4.9	-2.2	5.1	2.7	6.8	-3.5	4.0	-	-	0.6	6.4	-0.1	5.1	-2.9	6.1
PTB	-3.5	5.1	-5.1	7.7	-2.1	6.7	-3.2	6.1	-2.8	6.2	2.1	6.5	-4.1	5.3	-0.6	6.4	-	-	-0.7	6.2	-3.5	5.6
BEV	-2.8	4.8	-4.4	6.9	-1.4	5.4	-2.5	5.0	-2.1	5.1	2.8	6.6	-3.4	4.1	0.1	5.1	0.7	6.2	-	-	-2.8	6.0
OMH	0.0	4.1	-1.6	7.4	1.4	6.4	0.3	5.8	0.7	5.9	5.6	5.8	-0.6	4.9	2.9	6.1	3.5	5.6	2.8	6.0	-	-

Table 5. Degrees of equivalence and introductory text for the 25 kV radiation quality

Key comparison BIPM.RI(I)-K2

MEASURAND : **Air-kerma rate relative to the BIPM evaluation**
Radiation quality 25 kV

Key comparison reference value: the measurand is a ratio with reference value x_R = 1

The degree of equivalence of each laboratory *i* with respect to x_R is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty (k = 2), both dimensionless,
where $U_i = 2u_i$.

The degree of equivalence between two laboratories *i* and *j* is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty (k = 2), both dimensionless.
In evaluating $U_{ij} = 2u_{ij}$ for the table below, account is taken of correlations between u_i and u_j (see page 3 of the Summary Report).

Lab *j* ⇒

Lab *i* ⇓

Lab *i*	D_i / 10^{-3}	U_i / 10^{-3}	NPL D_{ij} / 10^{-3}	NPL U_{ij} / 10^{-3}	NIST D_{ij} / 10^{-3}	NIST U_{ij} / 10^{-3}	METAS D_{ij} / 10^{-3}	METAS U_{ij} / 10^{-3}	ENEA D_{ij} / 10^{-3}	ENEA U_{ij} / 10^{-3}	VNIIM D_{ij} / 10^{-3}	VNIIM U_{ij} / 10^{-3}	PTB D_{ij} / 10^{-3}	PTB U_{ij} / 10^{-3}	BEV D_{ij} / 10^{-3}	BEV U_{ij} / 10^{-3}	OMH D_{ij} / 10^{-3}	OMH U_{ij} / 10^{-3}
NPL	**1.0**	4.8	**-**	-	**6.3**	6.6	**0.1**	4.0	**3.9**	5.1	**4.7**	5.6	**3.2**	6.2	**2.6**	5.1	**0.4**	5.9
NIST	**-5.3**	5.3	**-6.3**	6.6	**-**	-	**-6.2**	5.7	**-2.4**	6.8	**-1.6**	7.0	**-3.1**	6.5	**-3.7**	6.6	**-5.9**	5.8
METAS	**0.9**	3.5	**-0.1**	4.0	**6.2**	5.7	**-**	-	**3.8**	4.0	**4.6**	4.6	**3.1**	5.3	**2.5**	4.1	**0.3**	4.9
ENEA	**-2.9**	5.0	**-3.9**	5.1	**2.4**	6.8	**-3.8**	4.0	**-**	-	**0.8**	5.6	**-0.7**	6.4	**-1.3**	5.1	**-3.5**	6.1
VNIIM	**-3.7**	5.3	**-4.7**	5.6	**1.6**	7.0	**-4.6**	4.6	**-0.8**	5.6	**-**	-	**-1.5**	6.6	**-2.1**	5.6	**-4.3**	6.4
PTB	**-2.2**	5.1	**-3.2**	6.2	**3.1**	6.5	**-3.1**	5.3	**0.7**	6.4	**1.5**	6.6	**-**	-	**-0.6**	6.2	**-2.8**	5.6
BEV	**-1.6**	4.8	**-2.6**	5.1	**3.7**	6.6	**-2.5**	4.1	**1.3**	5.1	**2.1**	5.6	**0.6**	6.2	**-**	-	**-2.2**	6.0
OMH	**0.6**	4.1	**-0.4**	5.9	**5.9**	5.8	**-0.3**	4.9	**3.5**	6.1	**4.3**	6.4	**2.8**	5.6	**2.2**	6.0	**-**	-

Table 6. Degrees of equivalence and introductory text for the 50 kVb radiation quality

Key comparison BIPM.RI(I)-K2

MEASURAND : **Air-kerma rate relative to the BIPM evaluation**
Radiation quality 50 kVb

Key comparison reference value: the measurand is a ratio with reference value $x_R = 1$

The degree of equivalence of each laboratory *i* with respect to x_R is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty ($k = 2$), both dimensionless,
where $U_i = 2u_i$.

The degree of equivalence between two laboratories *i* and *j* is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty ($k = 2$), both dimensionless.
In evaluating $U_{ij} = 2\,u_{ij}$ for the table below, account is taken of correlations between u_i and u_j (see page 3 of the Summary Report).

Lab *j* ⇒

Lab *i* ⇓

Lab *i*	D_i / 10^{-3}	U_i / 10^{-3}	GUM D_{ij} / 10^{-3}	GUM U_{ij} / 10^{-3}	NMi D_{ij}	NMi U_{ij}	NIST D_{ij}	NIST U_{ij}	METAS D_{ij}	METAS U_{ij}	ENEA D_{ij}	ENEA U_{ij}	VNIIM D_{ij}	VNIIM U_{ij}	PTB D_{ij}	PTB U_{ij}	BEV D_{ij}	BEV U_{ij}	OMH D_{ij}	OMH U_{ij}
GUM	-2.3	5.3	-	-	-1.6	5.2	3.8	7.0	-1.6	4.3	0.2	5.3	0.2	5.8	-0.1	6.7	-0.4	5.4	-3.0	6.4
NMi	-0.7	4.7	1.6	5.2	-	-	5.4	6.5	0.0	3.8	1.8	4.9	1.8	5.5	1.5	6.1	1.2	5.0	-1.4	5.8
NIST	-6.1	5.3	-3.8	7.0	-5.4	6.5	-	-	-5.4	5.7	-3.6	6.8	-3.6	7.0	-3.9	6.5	-4.2	6.6	-6.8	5.8
METAS	-0.7	3.5	1.6	4.3	0.0	3.8	5.4	5.7	-	-	1.8	4.0	1.8	4.6	1.5	5.3	1.2	4.1	-1.4	4.9
ENEA	-2.5	5.0	-0.2	5.3	-1.8	4.9	3.6	6.8	-1.8	4.0	-	-	0.0	5.6	-0.3	6.4	-0.6	5.1	-3.2	6.1
VNIIM	-2.5	5.3	-0.2	5.8	-1.8	5.5	3.6	7.0	-1.8	4.6	0.0	5.6	-	-	-0.3	6.6	-0.6	5.6	-3.2	6.4
PTB	-2.2	5.1	0.1	6.7	-1.5	6.1	3.9	6.5	-1.5	5.3	0.3	6.4	0.3	6.6	-	-	-0.3	6.2	-2.9	5.6
BEV	-1.9	4.8	0.4	5.4	-1.2	5.0	4.2	6.6	-1.2	4.1	0.6	5.1	0.6	5.6	0.3	6.2	-	-	-2.6	6.0
OMH	0.7	4.1	3.0	6.4	1.4	5.8	6.8	5.8	1.4	4.9	3.2	6.1	3.2	6.4	2.9	5.6	2.6	6.0	-	-

All D_{ij} and U_{ij} values are / 10^{-3}.

Table 7. Degrees of equivalence and introductory text for the 50 kVa radiation quality

Key comparison BIPM.RI(I)-K2

MEASURAND : **Air-kerma rate relative to the BIPM evaluation**
Radiation quality 50 kVa

Key comparison reference value: **the measurand is a ratio with reference value $x_R = 1$**

The degree of equivalence of each laboratory i with respect to x_R is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty ($k = 2$), both dimensionless,
where $U_i = 2u_i$.

The degree of equivalence between two laboratories i and j is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty ($k = 2$), both dimensionless.
In evaluating $U_{ij} = 2\,u_{ij}$ for the table below, account is taken of correlations between u_i and u_j (see page 3 of the Summary Report).

Lab j ⇨

Lab i ⇩			NRC		GUM		NMi		NPL		NIST		METAS		ENEA		VNIIM		PTB		BEV		OMH	
	D_i / 10^{-3}	U_i / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}	D_{ij} / 10^{-3}	U_{ij} / 10^{-3}
NRC	**0.2**	6.5	**-**	-	**1.8**	7.0	**3.2**	6.7	**1.8**	6.8	**4.6**	8.0	**1.0**	6.1	**2.9**	6.9	**1.2**	7.2	**1.3**	7.7	**2.1**	6.9	**-0.1**	7.4
GUM	**-1.6**	5.3	**-1.8**	7.0	**-**	-	**1.4**	5.2	**0.0**	5.3	**2.8**	7.0	**-0.8**	4.3	**1.1**	5.3	**-0.6**	5.8	**-0.5**	6.7	**0.3**	5.4	**-1.9**	6.4
NMi	**-3.0**	4.7	**-3.2**	6.7	**-1.4**	5.2	**-**	-	**-1.4**	4.9	**1.4**	6.5	**-2.2**	3.8	**-0.3**	4.9	**-2.0**	5.5	**-1.9**	6.1	**-1.1**	5.0	**-3.3**	5.8
NPL	**-1.6**	4.8	**-1.8**	6.8	**0.0**	5.3	**1.4**	4.9	**-**	-	**2.8**	6.6	**-0.8**	4.0	**1.1**	5.1	**-0.6**	5.6	**-0.5**	6.2	**0.3**	5.1	**-1.9**	5.9
NIST	**-4.4**	5.3	**-4.6**	8.0	**-2.8**	7.0	**-1.4**	6.5	**-2.8**	6.6	**-**	-	**-3.6**	5.7	**-1.7**	6.8	**-3.4**	7.0	**-3.3**	6.5	**-2.5**	6.6	**-4.7**	5.8
METAS	**-0.8**	3.5	**-1.0**	6.1	**0.8**	4.3	**2.2**	3.8	**0.8**	4.0	**3.6**	5.7	**-**	-	**1.9**	4.0	**0.2**	4.6	**0.3**	5.3	**1.1**	4.1	**-1.1**	4.9
ENEA	**-2.7**	5.0	**-2.9**	6.9	**-1.1**	5.3	**0.3**	4.9	**-1.1**	5.1	**1.7**	6.8	**-1.9**	4.0	**-**	-	**-1.7**	5.6	**-1.6**	6.4	**-0.8**	5.1	**-3.0**	6.1
VNIIM	**-1.0**	5.3	**-1.2**	7.2	**0.6**	5.8	**2.0**	5.5	**0.6**	5.6	**3.4**	7.0	**-0.2**	4.6	**1.7**	5.6	**-**	-	**0.1**	6.6	**0.9**	5.6	**-1.3**	6.4
PTB	**-1.1**	5.1	**-1.3**	7.7	**0.5**	6.7	**1.9**	6.1	**0.5**	6.2	**3.3**	6.5	**-0.3**	5.3	**1.6**	6.4	**-0.1**	6.6	**-**	-	**0.8**	6.2	**-1.4**	5.6
BEV	**-1.9**	4.8	**-2.1**	6.9	**-0.3**	5.4	**1.1**	5.0	**-0.3**	5.1	**2.5**	6.6	**-1.1**	4.1	**0.8**	5.1	**-0.9**	5.6	**-0.8**	6.2	**-**	-	**-2.2**	6.0
OMH	**0.3**	4.1	**0.1**	7.4	**1.9**	6.4	**3.3**	5.8	**1.9**	5.9	**4.7**	5.8	**1.1**	4.9	**3.0**	6.1	**1.3**	6.4	**1.4**	5.6	**2.2**	6.0	**-**	-

Appendix 1 – Note on change to published results of BIPM comparison with the NIST

The BIPM comparison with the NIST in low-energy x-rays was carried out in 1998 and the results are published in reports [6] and [7]. However, with effect from 1 January 2003, the NIST has revised its air-kerma standards. The changes to the standards are summarized in this appendix and the degrees of equivalence given in this report reflect the standards as they are currently disseminated.

In the low-energy x-ray range (10 kV to 100 kV) the NIST operates two free-air chamber standards. In the published comparison with the BIPM at the CCRI reference radiation qualities, the result for the 10 kV quality was derived from the NIST Lamperti chamber, whereas for the remaining qualities the Ritz chamber of the NIST was used. For both of these standards, new values for the photon-scatter correction factor, k_{sc}, have been introduced, as well as a new fluorescence correction factor, k_{fl}. The new values at the CCRI reference qualities are based on the calculations of Burns [15] using EGSnrc [16] and are given in Table A1 below.

The revised comparison results, taking into account the changes to the NIST and BIPM standards at each of the CCRI reference qualities, are given in the final row of the table. The comparison uncertainty is reduced from 0.0034 to 0.0026 mainly because of the lower uncertainty of the new correction factors, but also as a result of the greater correlation between the new values for the NIST and BIPM standards. It is the revised comparison results that are given in Table 2 and that have been used to evaluate the degrees of equivalence given in this report.

Table A1. Changes to results of BIPM comparison with the NIST as published in [6,7].

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Published 1998 comparison result NIST / BIPM	0.9950 (0.0034)	0.9943 (0.0034)	0.9949 (0.0034)	0.9938 (0.0034)	0.9956 (0.0034)
k_{sc} 2003	0.9978 (0.0007)	0.9967 (0.0007)	0.9966 (0.0007)	0.9973 (0.0007)	0.9975 (0.0007)
k_{sc} 1998	0.9960 (0.0020)	0.9941 (0.0020)	0.9944 (0.0020)	0.9956 (0.0020)	0.9963 (0.0020)
k_{fl} 2003	0.9960 (0.0006)	0.9962 (0.0004)	0.9961 (0.0004)	0.9975 (0.0004)	0.9981 (0.0004)
k_{fl} 1998	-	-	-	-	-
1998 result corrected for NIST changes	0.9928 (0.0029)	0.9931 (0.0029)	0.9932 (0.0029)	0.9930 (0.0029)	0.9949 (0.0029)
1998 result corrected for NIST and BIPM changes	**0.9958 (0.0026)**	**0.9944 (0.0026)**	**0.9947 (0.0026)**	**0.9939 (0.0026)**	**0.9956 (0.0026)**

Appendix 2 – Note on change to published results of BIPM comparison with the METAS

The BIPM comparison with the METAS in low-energy x-rays was carried out in 1998 and the results are published in report [8]. However, during the present analysis the published results were checked against the original data held in the comparison file at the BIPM and two errors in the published results were uncovered. These errors are summarized in this appendix and the degrees of equivalence given in this report correctly reflect the standards as they are disseminated.

The larger of the two errors is in the comparison result at the 50 kVb radiation quality, where the published value is $x_{\mathrm{METAS}} = 0.9994$. It is clear from the comparison file that there is a simple numerical error in the data analysis and that the published result should have been $x_{\mathrm{METAS}} = 0.9984$.

The smaller error arises at 10 kV where the published result is $x_{\mathrm{METAS}} = 0.9991$. Here, a correction factor 1.0003 was omitted. This factor corrects for the fact that the air-attenuation coefficient used for the comparison at 10 kV is the mean value measured at the BIPM over an attenuation length of 100 mm. However, the METAS standard has an attenuation length of only 90 mm, for which the mean air-attenuation coefficient is known from previous measurements to be larger, giving rise to an air-attenuation correction factor that is larger by 1.0003. The published result should have been $x_{\mathrm{METAS}} = 0.9994$.

These changes are shown in Table A2 below, together with the changes arising from the adoption of new correction factors for the BIPM standard.

Table A2. Changes to results of BIPM comparison with the METAS as published in [8].

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Published 1998 comparison result	0.9991 (0.0018)	0.9993 (0.0018)	0.9994 (0.0018)	0.9994 (0.0018)	0.9985 (0.0018)
1998 result corrected for errors	0.9994 (0.0018)	0.9993 (0.0018)	0.9994 (0.0018)	0.9984 (0.0018)	0.9985 (0.0018)
1998 result also corrected for BIPM changes	**1.0024** **(0.0017)**	**1.0006** **(0.0017)**	**1.0009** **(0.0017)**	**0.9993** **(0.0017)**	**0.9992** **(0.0017)**

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Figure 1. Graph of degrees of equivalence with the KCRV for the 10 kV radiation quality (as it appears in Appendix B of the MRA)

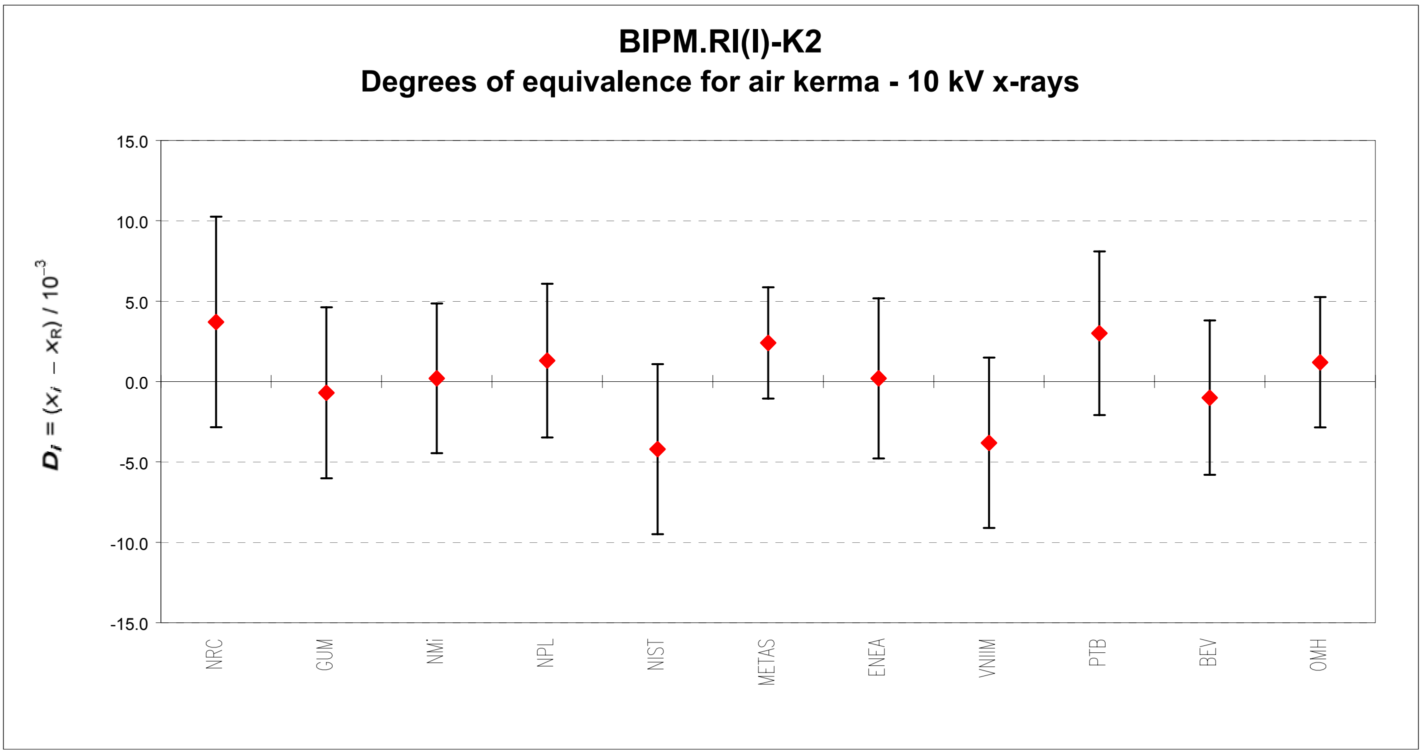

Figure 2. Graph of degrees of equivalence with the KCRV for the 30 kV radiation quality (as it appears in Appendix B of the MRA)

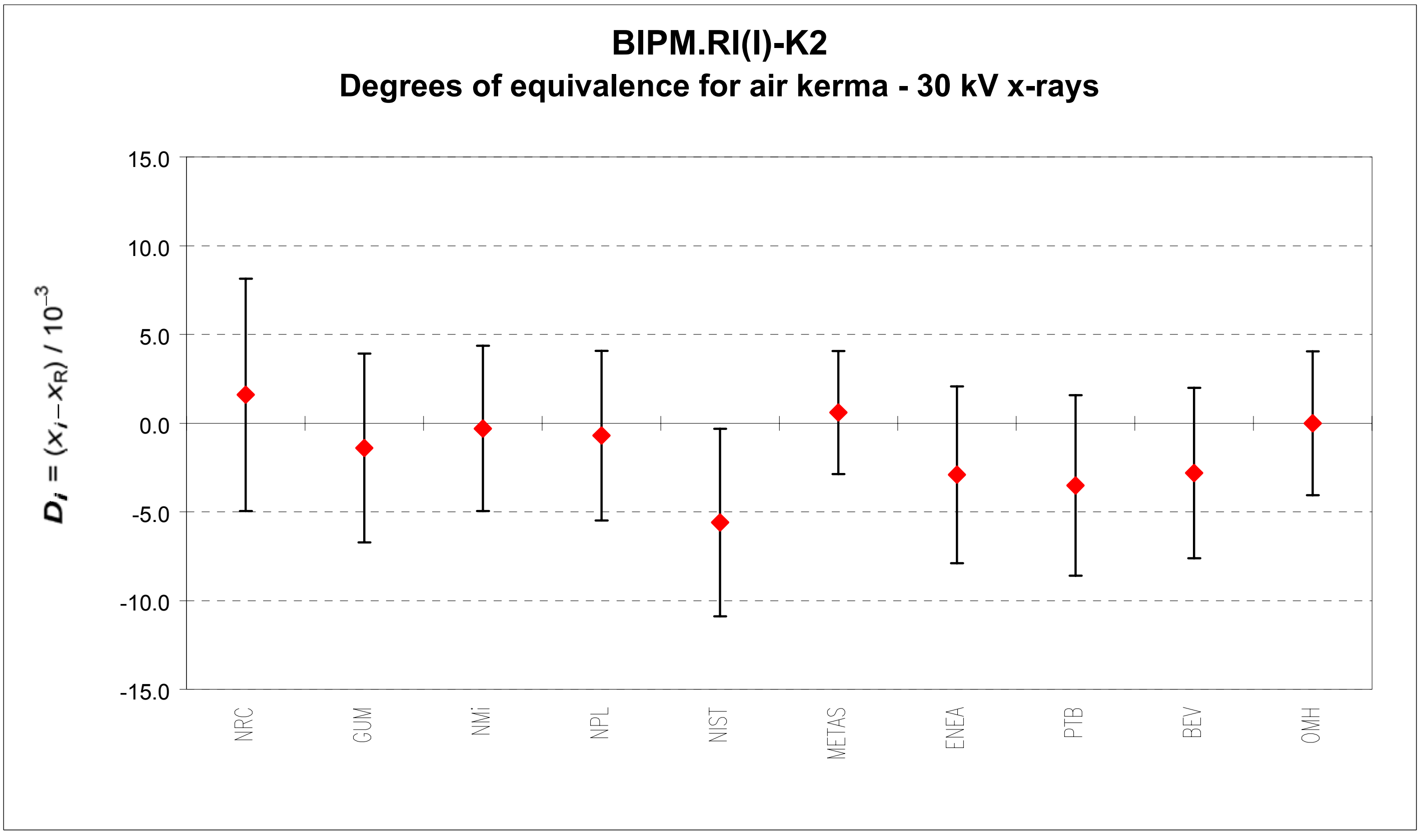

Figure 3. Graph of degrees of equivalence with the KCRV for the 25 kV radiation quality (as it appears in Appendix B of the MRA)

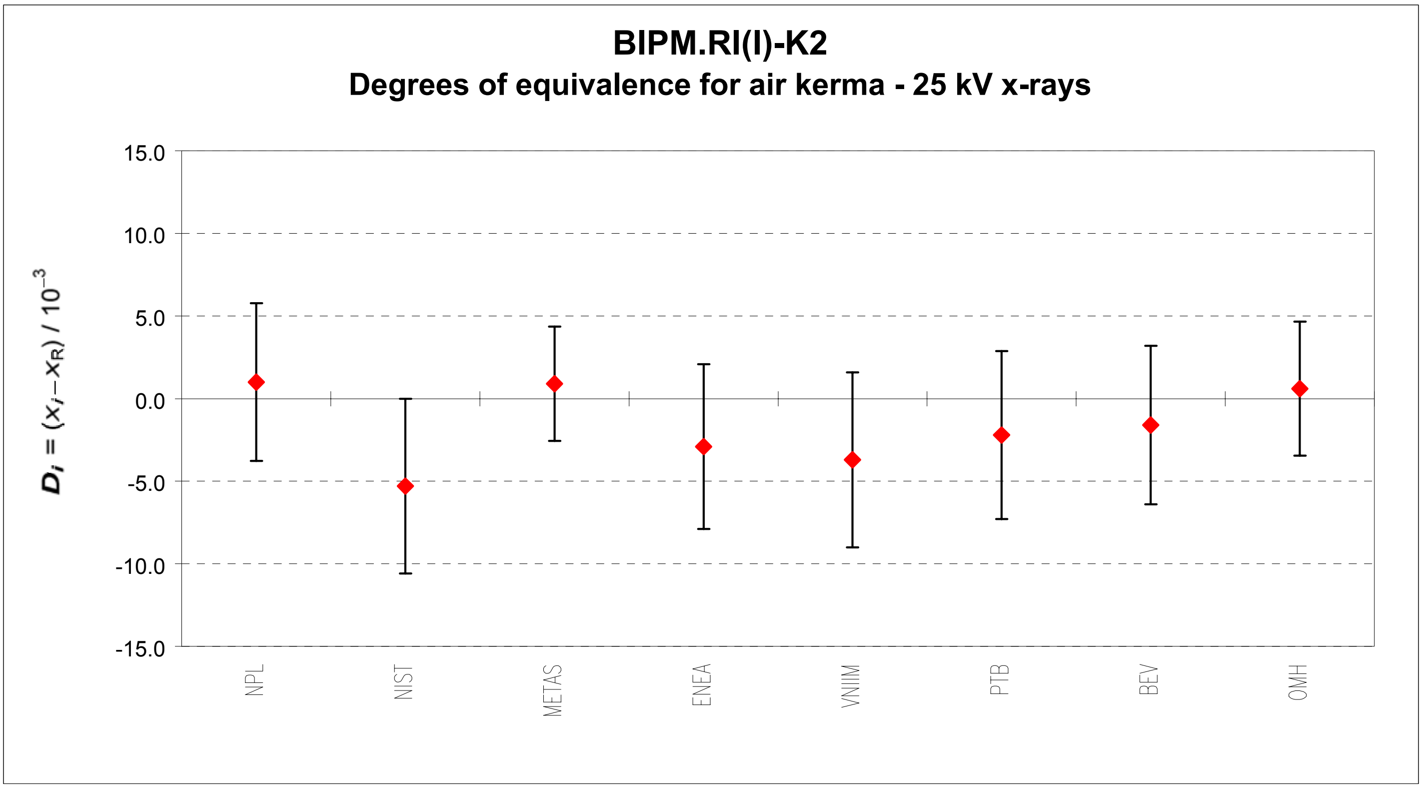

Figure 4. Graph of degrees of equivalence with the KCRV for the 50 kVb radiation quality (as it appears in Appendix B of the MRA)

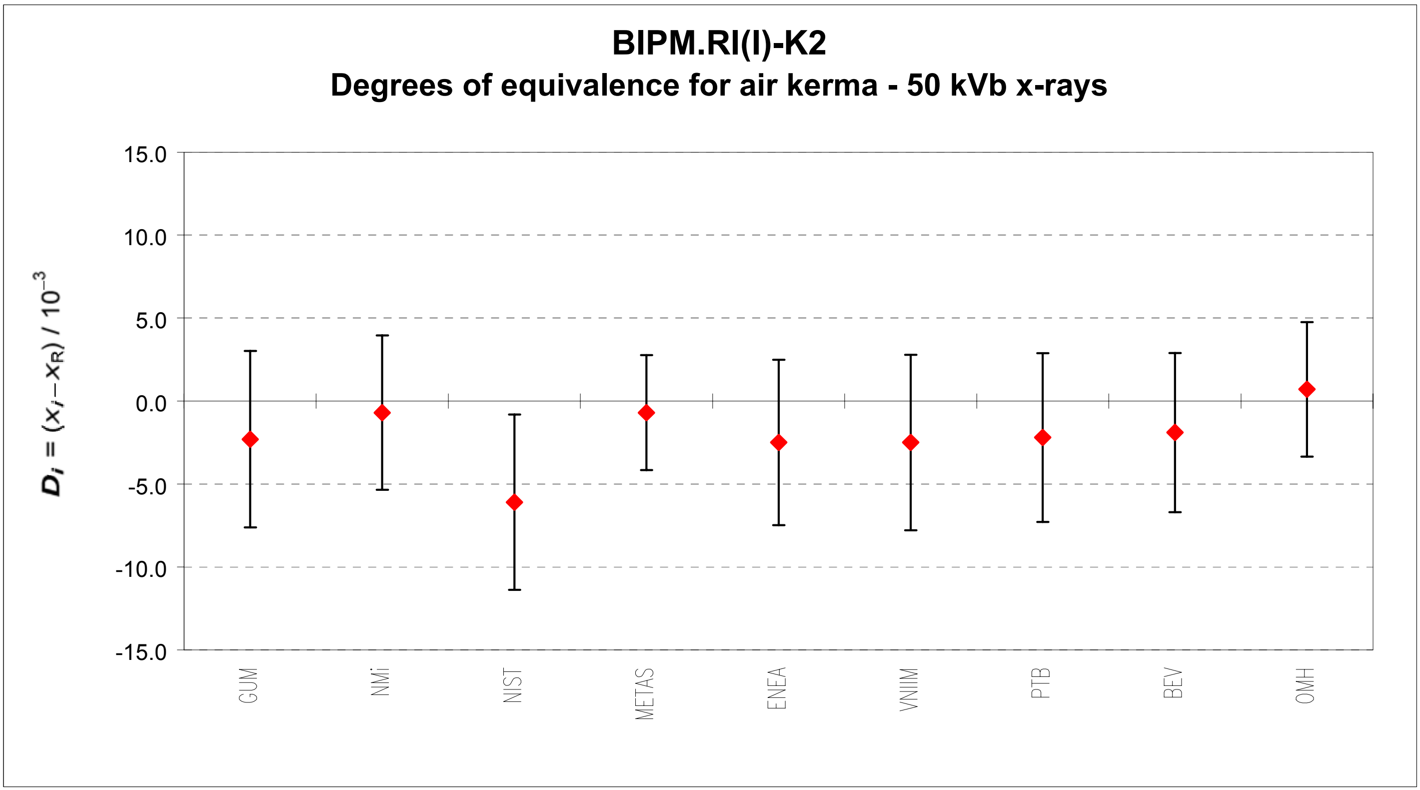

Figure 5. Graph of degrees of equivalence with the KCRV for the 50 kVa radiation quality (as it appears in Appendix B of the MRA)