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Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the MKEH, Hungary and the BIPM in low-energy x-rays

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Abstract A key comparison has been made between the air-kerma standards of the MKEH, Hungary and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement within the expanded uncertainty for the comparison of 4.1 parts in 10^3. No significant trend with radiation quality is observed. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

A direct comparison has been made between the air-kerma standards of the Hungarian Trade Licensing Office (MKEH), Hungary and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. Comparison measurements were also made using a transfer ionization chamber. The measurements at the BIPM took place in September 2011 using the reference conditions recommended by the CCRI [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

$$\dot{K} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W_{\mathrm{air}}}{e} \frac{1}{1-g_{\mathrm{air}}} \prod_i k_i \tag{1}$$

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 $\Pi\, k_{\mathrm{i}}$ 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].

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 in [2] and the changes made to certain correction factors in October 2003 and September 2009 given in [3, 4] and the references therein. The MKEH standard was previously compared with the BIPM standard in a direct comparison

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[1] For an air temperature $T \sim 293$ K, pressure P and relative humidity ~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 $k_{\mathrm{h}} = 0.9980$. In addition, a factor 1.0002 is included to account for the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

carried out at the BIPM in 2001, the results of which are reported in [5]. 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} (BIPM, 0 °C)	1.2930 kg m^{-3}	0.000 1
ρ_{air} (MKEH, 20 °C)	1.2048 kg m^{-3}	0.000 1
W_{air} / e	33.97 J C^{-1}	0.001 5

[a] u_i is the relative standard uncertainty.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	MKEH XE-3
Aperture diameter / mm	9.941	4.9995
Air path length / mm	100.0	63.7
Collecting length / mm	15.466	40.94
Electrode separation / mm	70	60.0
Collector width / mm	71	60.4
Measuring volume / mm^3	1200.4	803.69
Polarizing voltage / V	1500	1600

4. Comparison procedure

4.1 The BIPM irradiation facility and reference beam qualities

The comparison was carried out in the BIPM low-energy x-ray laboratory, which houses a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 1 mm beryllium. A beryllium filter of thickness 2.16 mm is added (for all radiation qualities) so that the half-value layer (HVL) of the present 10 kV radiation quality matches that of the original BIPM x-ray tube. 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 normalized for any deviation from the reference anode current. The resulting variation in the BIPM free-air chamber current over the duration of a comparison is normally not more than 3×10^{-4} in relative value. The radiation qualities used in the range from 10 kV to 50 kV are those recommended by the CCRI [1] and are given in Table 3 in ascending HVL from left to right.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 0.1 °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 from 47 % to 53 %.

Table 3. Characteristics of the BIPM reference radiation qualities

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV	10	30	25	50	50
Additional Al filtration / mm	0	0.2082	0.3723	1.0082	3.989
Al HVL / mm	0.037	0.169	0.242	1.017	2.262
$(\mu/\rho)_{air}$[a] / $cm^2\ g^{-1}$	14.84	3.66	2.60	0.75	0.38
$\dot{K}_{BIPM}$ / $mGy\ s^{-1}$	1.00	1.00	1.00	1.00	1.00

[a] Measured for an air path length of 100 mm using a variable-pressure tube.

4.2 Correction factors

The correction factors applied to the ionization current measured at each radiation quality, together with their associated uncertainties, are given in Table 4 for the BIPM standard and in Table 5 for the MKEH standard.

Table 4. Correction factors and uncertainties for the BIPM L-01 standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a[a]	1.1956	1.0451	1.0319	1.0091	1.0046	0.0002	0.0001
Scattered radiation k_{sc}[b]	0.9962	0.9972	0.9973	0.9977	0.9979	-	0.0003
Fluorescence k_{fl}[b]	0.9952	0.9971	0.9969	0.9980	0.9985	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001
Ion recombination k_s	1.0006	1.0007	1.0007	1.0007	1.0007	0.0001	0.0001
Polarity k_{pol}	1.0005	1.0005	1.0005	1.0005	1.0005	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0007
Diaphragm effects k_{dia}[c]	0.9999	0.9995	0.9996	0.9989	0.9984	-	0.0003
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	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.

[b] Values for k_{sc} and k_{fl} adopted in October 2003, based on Monte Carlo calculations.

[c] Correction factor k_{dia} for diaphragm transmission, scatter and fluorescence adopted September 2009, replacing the factor k_l for diaphragm transmission only. See reference [6].

The largest correction at low energies is that due to the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. The correction factor k_a is evaluated for the reference distance of 500 mm using the measured mass attenuation coefficients $(\mu/\rho)_{air}$ given in Table 3. 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. The value for k_a for the MKEH chamber at 10 kV has been increased by the factor 1.0011 to account for the larger mean air-attenuation coefficient for an air path length of 64 mm (the values given in Table 3 were measured at the BIPM for an air path length of 100 mm). This effect is negligible at the other radiation qualities. Ionization measurements 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.

Measurements using the BIPM standard were made using positive polarity only. A correction factor of 1.0005 was applied to correct for the known polarity effect in the standard. Similarly, measurements using the MKEH standard were made using positive polarity only and a correction factor of 1.0000(2) was applied. The ionization currents for the standards are corrected for ion recombination. The measured values for the ion recombination correction k_s for the BIPM standard are given in Table 4. For the MKEH standard, the values for k_s given in Table 5 for the BIPM air-kerma rates are derived from measurements at the MKEH.

Table 5. Correction factors and uncertainties for the MKEH XE-3 standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.1205	1.0285	1.0202	1.0058	1.0029	0.0002	0.0001
Scattered radiation k_{sc}	0.9970	0.9979	0.9980	0.9983	0.9985	-	0.0015
Fluorescence k_{fl}	0.9951	0.9968	0.9970	0.9980	0.9985	-	0.0007
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0002	-	0.0002
Ion recombination k_s	1.0004	1.0005	1.0005	1.0005	1.0005	0.0004	0.0001
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	0.0002	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0005
Diaphragm effects k_{dia} [c]	1.0000	1.0000	1.0000	0.9985	0.9981	-	0.0006
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	0.0001
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001

[a] Values for 293.15 K and 101.325 kPa and for measurements at the BIPM; each measurement is corrected using the air density measured at the time. For measurements at the MKEH, the larger uncertainties u_{iA} = 0.0005 and u_{iB} = 0.0010 apply.

[b] The values for k_{sc} differ from used those used in 2001 (by at most 2 parts in 10^4), while both k_{fl} and k_{dia} are new for the present comparison.

4.3 Chamber positioning and measurement procedure

The MKEH chamber was positioned close to the BIPM chamber and both remained fixed throughout the comparison; the alternation of measurements between chambers was carried out by displacement of the radiation source. Alignment on the beam axis was measured to around 0.1 mm and this position was reproducible to better than 0.01 mm. No correction is applied for the radial non-uniformity of the beam; for apertures of diameter 5 mm and 10 mm, the effect of the BIPM beam non-uniformity is around 2 parts in 10^4 and is included as an uncertainty in

Table 7. The reference plane for each chamber was positioned at 500 mm from the radiation source for all qualities. This distance was measured to 0.03 mm and was reproducible to better than 0.01 mm. The beam diameter in the reference plane is 45 mm for all qualities.

The air temperature for the MKEH chamber was assumed to be the same as that of the ambient air in the measurement laboratory. It is known that this temperature differs from that measured in the BIPM standard by at most 0.15 °C. Consequently, an additional uncertainty component of 5 parts in 10^4 is included for ionization current in Table 7. The leakage current was measured before and after each series of ionization current measurements and a correction made based on the mean of these leakage measurements. For the BIPM chamber the leakage current, relative to the ionization current of around 40 pA, was less than 1 part in 10^4 and for the MKEH chamber, with measured current around 30 pA, the relative leakage was similar.

For the MKEH standard, the standard uncertainty of the mean of a series of seven measurements, each with integration time 60 s, was around 2 parts in 10^4. Two such series were made for the comparison at each beam quality. For the BIPM standard, a similar series was made for each beam quality with a standard uncertainty also around 1 part in 10^4. For two of the radiation qualities (10 kV and 30 kV), the comparison was repeated on a subsequent day (the chambers remaining fixed in position) and the two comparison results for each quality agreed to better than 3 parts in 10^4 (included as an uncertainty for short-term reproducibility in Table 7).

5. Supporting measurements using a transfer chamber

A thin-window parallel-plate transfer ionization chamber belonging to the MKEH, type Radcal 10x5-6M serial number 8626, was calibrated in both laboratories to obtain an indirect comparison result. The chamber was used in each laboratory with a polarizing voltage of +250 V applied to the chamber window and with the red line around the chamber body positioned in the reference plane 500 mm from the source. No corrections were applied for ion recombination, as the dose rates at the two laboratories are the same, nor for radial non-uniformity, based on the assumption that the beam profiles will be similar at the two laboratories. The results are shown in Table 6 and include the correction k_Q for differences in the radiation qualities at the two laboratories; the only significant value is that at 10 kV, 0.9992 with a standard uncertainty of 0.0003.

Table 6. Results for the transfer chamber Radcal 10x5-6M sn 8626

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$N_{K,\mathrm{MKEH}}$ (pre-BIPM)	4.910	4.816	4.806	4.834	4.889
$N_{K,\mathrm{MKEH}}$ (post-BIPM)	4.891	4.810	4.793	4.831	4.886
σ_{dist} (relative)	0.0027	0.0009	0.0019	0.0005	0.0005
$N_{K,\mathrm{BIPM}}$	4.876	4.821	4.809	4.828	4.878
$N_{K,\mathrm{MKEH}}$(mean) /$N_{K,\mathrm{BIPM}}$	1.0050	0.9984	0.9981	1.0009	1.0019
k_Q	0.9992	1.0000	1.0001	0.9999	1.0001
Indirect comparison result	1.0042	0.9984	0.9982	1.0008	1.0020

6. Uncertainties

The uncertainties associated with the primary standards and with the results of the comparison are listed in Table 7. The uncertainties associated with the measurement of the ionization current and with chamber positioning are those that apply to measurements at the BIPM.

The combined standard uncertainty u_c of the ratio $\dot{K}_{\mathrm{MKEH}}/\dot{K}_{\mathrm{BIPM}}$ takes into account correlation in the type B uncertainties associated with the humidity correction and the physical constants. Correlation in the values for k_{sc}, k_{fl}, k_e and k_{dia} is taken into account in an approximate way by assuming half of the uncertainty value for each factor at each laboratory. This is consistent with the analysis presented in [7].

Table 7. Uncertainties associated with the comparison results

Standard	BIPM		MKEH	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0002[a]	0.0005
Positioning	0.0001	0.0001	-	- [a]
Volume	0.0003	0.0005	0.0010	0.0005
Correction factors (excl. k_h)	0.0003	0.0010	0.0005	0.0019
Humidity k_h	-	0.0003	0.0000	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}_{\mathrm{Standard}}$	0.0005	0.0019	0.0011	0.0025
	0.0020		0.0028[a]	
Radial non-uniformity	0.0002			
Short-term reproducibility	0.0003			
$\dot{K}_{\mathrm{MKEH}}/\dot{K}_{\mathrm{BIPM}}$	$u_c = 0.0020$[b]			

[a] For measurements at the MKEH, $u_{iA} = 0.0007$ for ionization current and $u_{iB} = 0.0010$ for positioning. Including also the uncertainty values for attenuation noted in the footnote to Table 5, the uncertainty of the air-kerma determination at the MKEH is 0.0032, rather than the value 0.0028 tabulated here. It is the higher value that appears as $u_{\mathrm{Lab}i}$ in the KCDB.

[b] Takes account of correlation in the type B uncertainties.

7. Results and discussion

The comparison results are given in Table 8. General agreement at the level of 2 to 3 parts in 10^3 is observed, consistent with the standard uncertainty for the comparison of 2.0 parts in 10^3 given in Table 7. There is no evidence of a trend in the results for the different radiation qualities, although the result for 25 kV is notably more than 1 part in 10^3 higher and that at 50 kVa slightly lower.

Also shown in Table 8 are the results of the direct comparison in 2001 between the two standards [5]. These results are taken from the key comparison database, where they are already updated for changes to the BIPM standard, and are further updated here for changes to the MKEH standard, namely small changes in k_{sc} and the introduction of k_{fl} and k_{dia}. This analysis shows the ratio of the standards to be stable at the level of 1 part in 10^3 over the past ten years.

The results of the indirect comparison using the transfer chamber given in Table 7 are in good agreement for the 30 kV and 25 kV qualities, and are within 3 parts in 10^3 for 50 kVb. However, the indirect results for 10 kV and 50 kV are both higher by 6 or 7 parts in 10^3. While the result at 10 kV might be related to the difficulty in determining the attenuation correction, the discrepancy at 50 kVa is a surprising result and no explanation has been found.

Table 8. Comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$\dot{K}_{\mathrm{MKEH}}/\dot{K}_{\mathrm{BIPM}}$	0.9973	0.9975	0.9988	0.9974	0.9966
Revised 2001 comparison	0.9963	0.9974	0.9983	0.9982	0.9979

8. 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 [7]. 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 and including those of the present comparison, are shown in Table 9 and in Figure 1.

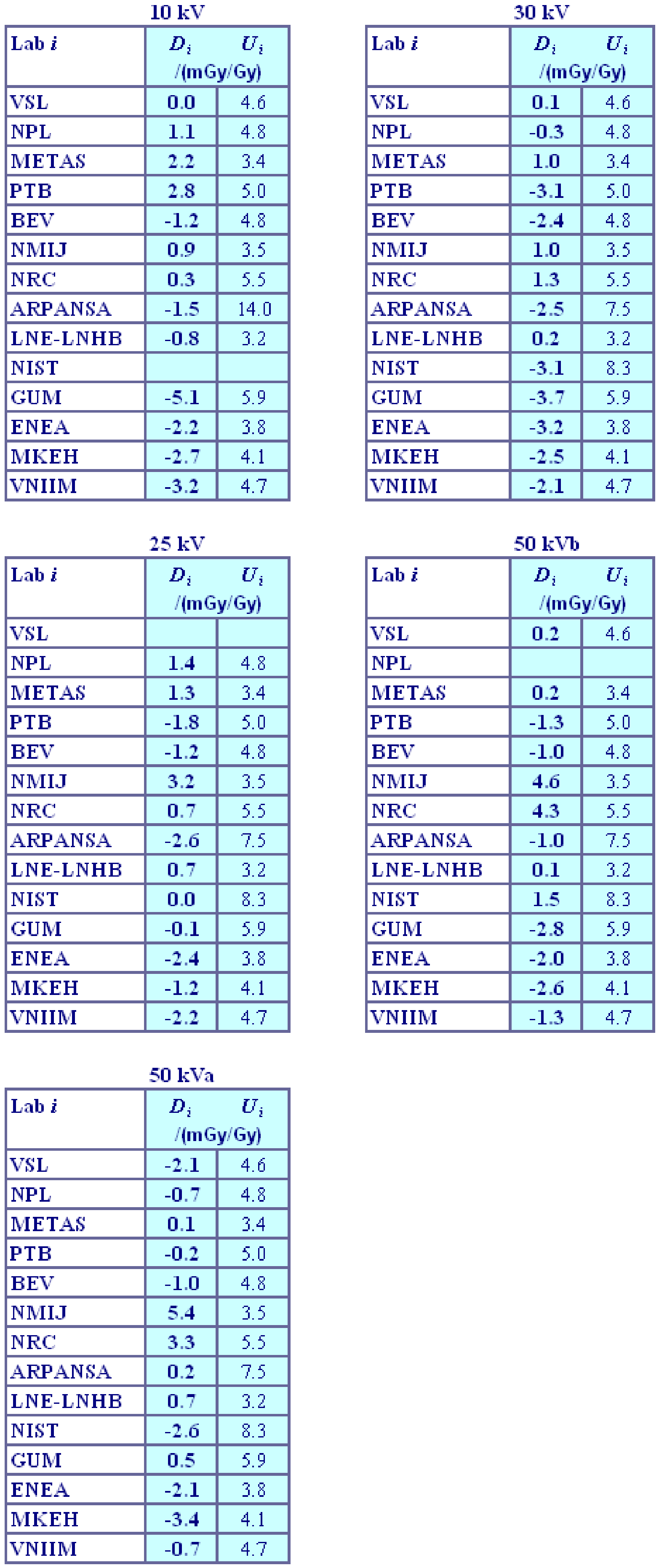
When required, the degree of equivalence between two laboratories i and j can be evaluated as the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\,u_{ij}$, both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j [7].

9. Conclusions

The key comparison BIPM.RI(I)-K2 for the determination of air kerma in low-energy x-rays shows the standards of the MKEH and the BIPM to be in agreement within the expanded uncertainty for the comparison of 4.1 parts in 10^3. The results are in good agreement with those of the 2001 comparison between the two standards if the changes made to the standards are taken into account. Indirect comparison results using a transfer chamber are in reasonable agreement for the intermediate qualities, but at 10 kV and 50 kVa show a discrepancy of 6 to 7 parts in 10^3.

Degrees of equivalence, including those for the MKEH, are presented for entry in the BIPM key comparison database. Note that the data presented in the tables, while correct at the time of publication of the present report, become out of date as laboratories make new comparisons with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database.

Table 9. Degrees of equivalence. For each laboratory i, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i. Tables formatted as they appear in the BIPM key comparison database.



10 kV

Lab i	D_i	U_i
	/(mGy/Gy)	
VSL	0.0	4.6
NPL	1.1	4.8
METAS	2.2	3.4
PTB	2.8	5.0
BEV	-1.2	4.8
NMIJ	0.9	3.5
NRC	0.3	5.5
ARPANSA	-1.5	14.0
LNE-LNHB	-0.8	3.2
NIST		
GUM	-5.1	5.9
ENEA	-2.2	3.8
MKEH	-2.7	4.1
VNIIM	-3.2	4.7

30 kV

Lab i	D_i	U_i
	/(mGy/Gy)	
VSL	0.1	4.6
NPL	-0.3	4.8
METAS	1.0	3.4
PTB	-3.1	5.0
BEV	-2.4	4.8
NMIJ	1.0	3.5
NRC	1.3	5.5
ARPANSA	-2.5	7.5
LNE-LNHB	0.2	3.2
NIST	-3.1	8.3
GUM	-3.7	5.9
ENEA	-3.2	3.8
MKEH	-2.5	4.1
VNIIM	-2.1	4.7

25 kV

Lab i	D_i	U_i
	/(mGy/Gy)	
VSL		
NPL	1.4	4.8
METAS	1.3	3.4
PTB	-1.8	5.0
BEV	-1.2	4.8
NMIJ	3.2	3.5
NRC	0.7	5.5
ARPANSA	-2.6	7.5
LNE-LNHB	0.7	3.2
NIST	0.0	8.3
GUM	-0.1	5.9
ENEA	-2.4	3.8
MKEH	-1.2	4.1
VNIIM	-2.2	4.7

50 kVb

Lab i	D_i	U_i
	/(mGy/Gy)	
VSL	0.2	4.6
NPL		
METAS	0.2	3.4
PTB	-1.3	5.0
BEV	-1.0	4.8
NMIJ	4.6	3.5
NRC	4.3	5.5
ARPANSA	-1.0	7.5
LNE-LNHB	0.1	3.2
NIST	1.5	8.3
GUM	-2.8	5.9
ENEA	-2.0	3.8
MKEH	-2.6	4.1
VNIIM	-1.3	4.7

50 kVa

Lab i	D_i	U_i
	/(mGy/Gy)	
VSL	-2.1	4.6
NPL	-0.7	4.8
METAS	0.1	3.4
PTB	-0.2	5.0
BEV	-1.0	4.8
NMIJ	5.4	3.5
NRC	3.3	5.5
ARPANSA	0.2	7.5
LNE-LNHB	0.7	3.2
NIST	-2.6	8.3
GUM	0.5	5.9
ENEA	-2.1	3.8
MKEH	-3.4	4.1
VNIIM	-0.7	4.7

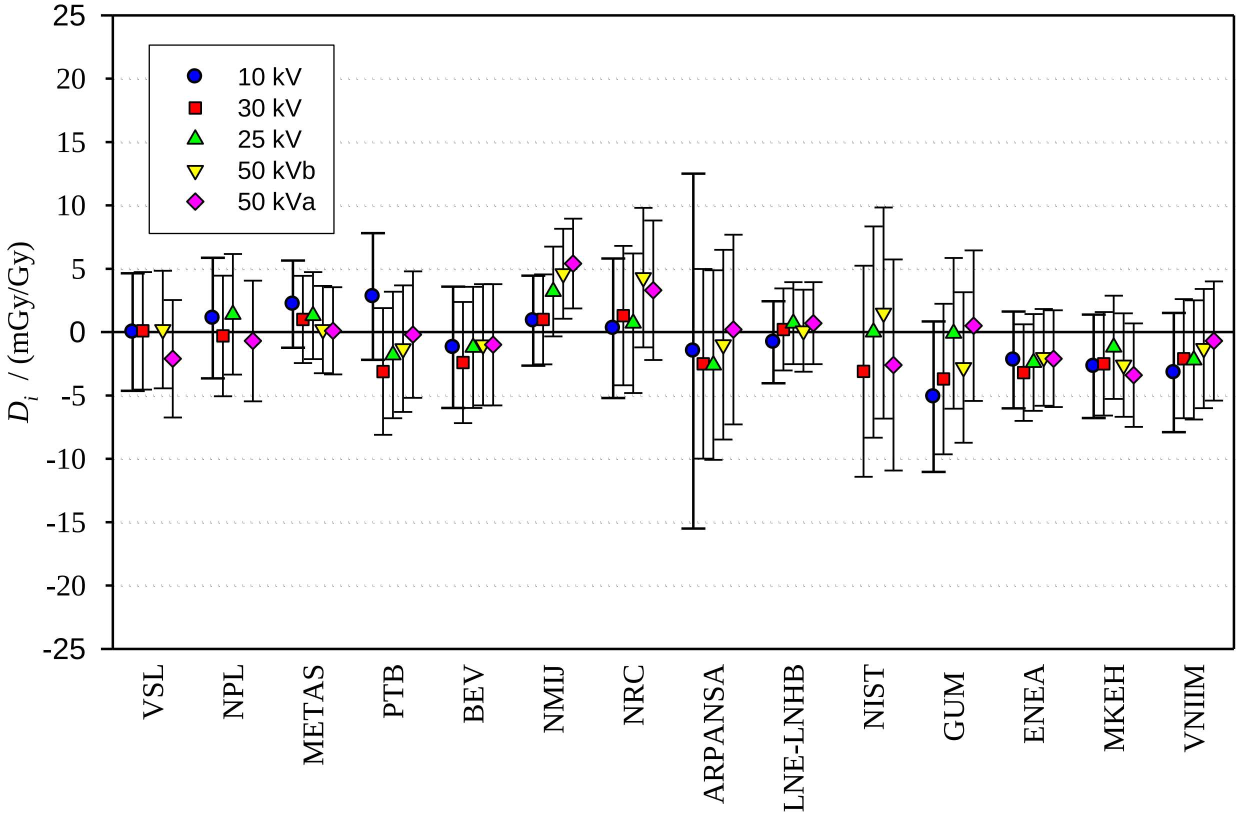


Figure 1. Degrees of equivalence for each NMI *i* with respect to the key comparison reference value

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