Comparison of the air kerma standards of the NMi and the BIPM in the low energy x-ray range

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Abstract

A comparison between the air kerma standards of the NMi and the BIPM has been performed in low energy x-rays by direct comparison of the primary standards.
The results show that the air kerma standards of the NMi and the BIPM agree within 0.4 %. Compared to the results of 1968, the results of the present comparison are closer to unity, the changes in time being less than 0.2 %.

During and after the comparison NMi has determined new values for the correction factors for scattered radiation, electron loss and transmission through the diaphragm and front wall of their standard using Monte Carlo methods[1]. The influences of the calculated new values on the results of this comparison are shown in appendix I.

Although not yet adopted, these new values improve the results of this comparison, giving agreement within 0.1 %.

Contents

1. Introduction

In the past few years, the international comparability of the air kerma standards of the Nederlands Meetinstituut (NMi) for ^{60}Co gamma radiation and for medium-energy x-rays has been established by comparisons with the standards of the Bureau International des Poids et Mesures (BIPM) [2]. For low energy x-rays, the previous comparison of the NMi and BIPM air kerma standards was performed in 1968 [3]. As a result of this comparison, a study of the correction for photon scatter in free-air ionization chambers was performed by Somerwil [4]. In 1994, the NMi standards were moved from Bilthoven to a new location in Utrecht where a new calibration facility was brought into use.

To confirm the stability of the standards of the NMi and the BIPM a new comparison was made. The present report describes the results of the new comparison.

Recently a new method for determining the correction factors for free-air ionization chambers based on the Monte Carlo method was carried out. This comparison made it be able to directly assess the effect of introducing new correction factors for the NMi standard,

2. Materials and methods

The comparisons were made according to the reference conditions recommended by Section I of the Comité Consultatif des Rayonnements Ionisants (CCRI) [5], formerly known as the CCEMRI. The BIPM standard is described in [6] and no further details are given in this report. The NMi standard is a parallel-plate free-air ionization chamber similar to that designed by Greening [7]. The most important characteristics of the NMi standard are given in table 1.

Table 1: Characteristics of the NMi air kerma standard for low energy x-rays

Plate separation *d*	4.0 cm
Collecting plate height	5.2 cm
Collecting plate length *L*	1.0018 cm
Limiting aperture diameter	0.4996 cm
Measuring volume	0.1964 cm^3
Air attenuation path length	3.85 cm

The NMi standard was positioned close to the BIPM standard, on the same lathe bench. The temperature for the NMi standard was measured with a thermistor placed on top of the chamber. The polarising voltage applied to the NMi standard was 1000 V. Measurements with negative and positive polarities were made to correct for polarity effects. The polarity effect varied between 0.04% and 0.17% for the BIPM standard and between 0.1% and 0.3% for the NMi standard. The x-ray tube was displaced so that the beam axis coincided with that of one chamber or the other. Measurements with the NMi standard were made immediately before and after the measurements with the BIPM standard. Despite the very small variations, of the order of 10^{-4}, in the accelerating voltage and x-ray tube current, some drift in the x-ray output still occurs. As a result, the measured polarity effect for the NMi standard combines the effects of polarity and drift. For both standard chambers, the air kerma rate, $\dot{K}$ EMBED, is determined from:

$$\dot{K} = \frac{I}{\rho V} \frac{W}{e} \frac{1}{1-\bar{g}} \prod k_i$$

where

I is the ionization current measured by the standard,

ρ is the dry air density,

V is the effective measuring volume,

W is the average energy spent by an electron of charge e to produce an ion pair in dry air,

$\bar{g}$ is the fraction of electron energy lost by bremsstrahlung,

$\prod k_i$ is the product of the correction factors to be applied to the standard.

The correction factors k_i for the NMi standard and for the BIPM reference x-ray qualities used in this comparison are given in table 2.

Table 2: Correction factors for the NMi standard and for the BIPM reference qualities

Correction factors		10 kV	30 kV	50 kV(b)	50 kV(a)
k_{sc}	Scattered radiation	0.996	0.997	0.998	0.998
k_e	Electron loss	1.000	1.000	1.002	1.005
k_a	Air attenuation[(1)]	1.0720	1.0163	1.0035	1.0018
k_s	Recombination loss	1.0005	1.0007	1.0006	1.0005
k_h	Humidity	0.998	0.998	0.998	0.998

[(1)] at 20 °C and 101.325 kPa

The correction for scattered radiation was calculated using the following empirical relation suggested by Lamperti *et al* [8], which is based on data of Ritz [9]:

$$k_{sc} = 0.9975 + 1.034\ 10^{-3} \log_{10} (HVL)$$

where HVL is the half-value layer of the x-ray quality expressed in mm of Al. The uncertainty stated by Lamperti *et al.* was 0.07%[1]. According to Somerwil [4] this relation over-estimates the effect for the 10 kV and 30 kV beam qualities. However, since in the study of Somerwil no exact data were given for the adjustment of the correction factors, the original correction factors for scattered radiation were used for this comparison.

The corrections for electron loss for the two 50 kV qualities were estimated from the data of Ritz [9]. The uncertainty of reading these correction factors from the graphs of Ritz was estimated to be 0.1%. Within this uncertainty, the correction factor for electron loss for the 10 kV and 30 kV qualities was taken to be unity.

For the 30 kV and both 50 kV qualities, the air attenuation correction was calculated from the air path length of the NMi standard (38.5 mm) and the air attenuation coefficients normally used by the BIPM. However, for the 10 kV quality, the air attenuation correction is very large, and the air attenuation coefficient varies rapidly with the length of the air path. Therefore, the attenuation coefficient for the NMi standard was measured during the comparison using the vacuum tube method. This resulted in an air attenuation coefficient for an air path length of 38.5 mm of 1.805 m^{-1} and a nominal air attenuation correction of 1.0720 for the NMi standard (both at 20 °C and 101.325 kPa).

1 All uncertainties in this report refer to one standard uncertainty, unless stated otherwise

As a check, the air attenuation coefficient for the 10 kV quality for the NMi standard was experimental determined by the displacement method. This resulted in an air attenuation coefficient of 1.795 m^{-1}, which is in good agreement with the result of the vacuum tube method.

The correction for recombination loss was calculated according to the equation given by Boutillon [10]:

$$ks = 1 + B\,d/V \;+ m^2 (g/V^2) Is$$

where

d	=	plate separation (4.0 cm for NMi standard)
V	=	polarising voltage (1000 V for NMi standard)
$B\,d/V$	=	initial part of the recombination ($4.64\ 10^{-4}$, using B=0.116 from Boutillon [10])
m^2	=	volume recombination parameter ($3.97\ 10^{14}$ s m^{-1} C^{-1} V^2, from Boutillon [10])
g	=	geometric factor ($d^2 / 2\pi L$) for parallel-plate free-air chamber (0.025419 m for NMi)
Is	=	ionisation current at saturation

From the uncertainty estimate of Boutillon, the relative standard uncertainty in the correction for recombination derived using this equation for the NMi standard amounts to less than 0.01%.

During the comparison, the relative humidity was in the range from 40% to 50%. The correction factor k_h was applied to the ionization current measured by both standards. The air temperature was around 22 °C. During each series of measurements, the air temperature was stable to better than 0.03 °C. The measured ionization current was normalized to 20 °C and 101.325 kPa.

For both standards, the BIPM electrometer was used to measure the current. The same capacitor was used for all measurements. The leakage current was negligible, being less than 0.01% for both standards.

The short-term relative standard uncertainty of the mean ionization current varied between 0.01% and 0.05% for the BIPM standard, and between 0.01% and 0.06% for the NMi standard.

The uncertainties in the measurement of the air kerma rate in the BIPM beam, measured by the NMi standard and the BIPM standard, respectively, are summarized in table 3. Although some uncertainties may vary slightly between the different beam qualities, the uncertainties are assumed to be the same for all beam qualities. The BIPM uncertainties were taken from Boutillon [11].

Table 3: Estimated relative standard uncertainties in the NMi and BIPM determinations of air kerma rate for low-energy x-rays (10 kV to 50 kV) at 50 cm distance from the x-ray tube. s_i represents the relative uncertainty estimated by statistical methods, type A, u_i represents the relative uncertainty estimated by other means, type B. Uncertainties are given in percent.

		NMi values		BIPM values	
		s_i	u_i	s_i	u_i
Physical constants					
Dry air density (273.15 K, 101 325 Pa)			≤ 0.01		≤ 0.01
W/e			0.15		0.15
$\bar{g}$			≤ 0.01		≤ 0.01
Correction factors					
k_{sc}	scattered radiation		0.07		0.07
k_e	electron loss		0.1		≤ 0.01
k_s	recombination loss		0.01	0.02	0.01
k_a	air attenuation	0.03	≤ 0.01	0.03	≤ 0.01
k_d	field distortion		≤ 0.01		0.07
k_1	transmission through edges of diaphragm		-		≤ 0.01
k_p	transmission through walls of standard		-	≤ 0.01	
k_h	humidity		0.03		0.03
Measurement of $\frac{I}{\rho V}$					
V	volume		0.1	0.03	0.05
I	ionization current	0.06		0.05	
	correction concerning ρ (temperature, pressure, air compressibility)	0.03	0.04	0.03	0.02
	polarity effects		0.08		
Positioning at the same distance			0.02		
Relative uncertainty on $\dot{K}$					
	quadratic sum	0.07	0.23	0.08	0.19
	combined uncertainty	0.24		0.20	

3. Results

The results of BIPM comparisons, R_{NMi}, are expressed in the form:

$$R_{\text{NMi}} = \frac{\dot{K}_{\text{NMi}}}{\dot{K}_{\text{BIPM}}}$$

where

$\dot{K}_{\text{NMi}}$ and $\dot{K}_{\text{BIPM}}$ are the air kerma rates in the BIPM beam, measured by the NMi standard and the BIPM standard, respectively. The R_{NMi} values for the four BIPM reference qualities used in this comparison are shown in table 4, together with the results of the comparison made in 1968.

Table 4: Results of the comparisons of 1968 and 1996

	R_{NMi} (1968)	R_{NMi} (1996)
10 kV	0.9964	0.9972
30 kV	0.9964	0.9984
50 kV(b)	-	0.9984
50 kV(a)	0.9948	0.9963

The results show that the air kerma standards of the NMi and the BIPM agree within 0.4%. Compared to the results of 1968, the results of the present comparison are closer to unity, but the changes with time are less than 0.2%.

The uncertainty in R_{NMi} is equal to the combined uncertainty of $\dot{K}_{\text{NMi}}$ and $\dot{K}_{\text{BIPM}}$, but excluding the uncertainties due to physical constants and correction factors which are the same for both standards (such as the uncertainty of W/e, k_h and the Type B uncertainty of I; correlation in the values used for the scatter correction k_{sc} have been neglected). Following this approach and using a coverage factor of 2, an expanded uncertainty of 0.46% in R_{NMi} is obtained.

4. Conclusion

The results of the comparison show that the air kerma standards of the NMi and the BIPM for low-energy x-rays agree within 0.4%, which is within the expanded uncertainty of the comparison result. The results are consistent at the 0.2% level with the results of the comparison made in 1968. This confirms the stability of the standards over a 28 year period.

Appendix I: Result of the comparison if MC-based correction factors are used

Recently, both the NMi and the BIPM have determined the correction factors for scattered radiation and electron loss using Monte Carlo methods, although these new values have not yet been adopted. The NMi has also determined values for the transmission through the diaphragm and front wall of their standard. The proposed adoption by the NMi of the new values for these correction factors for their standard will have an effect on the results of this comparison, although the results presented above are useful in showing the stability of both standards since 1968.The newly calculated correction factors for the NMi and BIPM standards, for the BIPM reference x-ray qualities, are shown in table 5.

Table 5: Newly calculated correction factors for the NMi and BIPM standards, for the BIPM reference qualities for low-energy x-rays

Correction factor		10 kV	30 kV	50 kV(b)	50 kV(a)
NMi standard					
k_{sc}	scattered radiation	0.9978	0.9985	0.9989	0.9991
k_e	electron loss	1.0000	1.0000	1.0025	1.0076
k_{tr}	transmission	1.0000	1.0000	0.9999	0.9996
BIPM standard					
k_s	scattered radiation	0.9958	0.9971	0.9977	0.9979
k_e	electron loss	1.0000	1.0000	1.0000	1.0000

For the NMi standard, the most pronounced change is that of the correction for electron loss for the 50 kV qualities. For the most filtered 50 kV quality the change amounts to 0.3 %. The changes to the correction for scattered radiation are close to those suggested by Somerwil [4].

Table 6 shows the results of the comparison, if the new correction factors were adopted by both laboratories.

Table 6: Results of the 1996 comparison, calculated with the present correction factors and the new correction factors

	R_{NMi} present correction factors	R_{NMi} New correction factors
10 kV	0.9979	0.9997
30 kV	0.9984	0.9999
50 kV(b)	0.9984	0.9997
50 kV(a)	0.9963	0.9995

For all beam qualities, the results are closer to unity if the MC-based correction factors are applied.

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