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A study of the response of ionization chambers to mammography beams

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Abstract

Some simulated mammography radiation beams have been established at the BIPM using a low-energy x-ray tube with a tungsten anode and molybdenum as a filter. The response of two ionization chambers of different types to these beams is compared with that obtained in mammography beams at the PTB and the NMi which were produced with x-ray tubes with molybdenum anodes and molybdenum filters. The relative differences between the chamber responses to these two different types of beams were less than 7×10^{-3} which implies the uncertainty for the transfer of a calibration from one type of beam to the other.

1. Introduction

New radiation beam qualities have been established at the BIPM using the tungsten-anode low-energy x-ray tube with molybdenum filters (W/Mo beams) to simulate the radiation beams used in clinical mammography. The latter are usually produced using an x-ray tube with molybdenum or rhodium anodes filtered by thin foils of molybdenum or rhodium, sometimes with aluminium added.

Two ionization chambers of type Radcal RC6M and Exradin A11TW have been calibrated in the BIPM W/Mo beams and the responses are compared with those obtained from calibration in Mo/Mo mammography beams. An additional calibration at the CCRI 25 kV quality [1] has been made at all the institutes to consider any differences in their primary standards.

This study is a step towards establishing a mammography comparison and calibration facility at the BIPM.

2. Calibration of the ionization chambers

Two different types of ionization chamber currently used for mammography dosimetry were chosen for this study. A Radcal 10X5-6M (sn 9112) and an Exradin A11TW (sn 30061) were calibrated in terms of air kerma in the W/Mo beams at the BIPM and in the Mo/Mo beams at the Physikalisch-Technische Bundesanstalt (PTB, Germany) and the Nederlands Meetinstituut (NMi, Netherlands).

The air kerma rate is determined at each laboratory using its own primary air kerma standard 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 V is the measuring volume, 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 mean fraction of the initial electron energy lost by bremsstrahlung production in air, and $\Pi\ k_{\text{i}}$ is the product of the correction factors to be applied to the standard. The BIPM standard is described in [2] and [3]; details of the PTB and the NMi standards can be found in [4] and [5], respectively. The NMi standard is similar to the one described by Greening [6].

The calibration coefficient N_K for an ionization chamber is given by the relation

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

where $\dot{K}$ is the air kerma rate determined by the standard (1) and I_{ch} is the ionization current measured by the chamber with the associated current-measuring system. The current I_{ch} is normalized to the standard conditions of air temperature and pressure chosen for the calibrations (T = 293.15 K, P = 101 325 Pa) and a relative humidity of 50 %.

2.1 Irradiation facilities and 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. The generating potential 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.

A combination of the tungsten anode with a molybdenum filter of 0.06 mm thickness and different tube voltages was used to simulate clinical mammography radiation beams. Information on the measuring conditions used for calibration of ionization chambers at the BIPM and the establishment of the W/Mo radiation qualities is detailed in [3] and [7], respectively.

The PTB mammographic beam qualities are produced with a unipolar x-ray tube with a molybdenum anode combined with a constant potential generator. The inherent filtration is 1 mm beryllium and the molybdenum filtration is 0.03 mm. Radiation qualities are established for tube voltages in the range from 20 kV to 50 kV.

The PTB CCRI radiation qualities are also realized with a unipolar x-ray tube combined with a constant potential generator. The inherent filtration is 1 mm beryllium.

For both x-ray facilities the high voltage was measured invasively with a voltage divider manufactured and calibrated at PTB. A transmission-type monitor chamber manufactured at PTB was used at both facilities to normalize the x-ray output.

The NMi facility for low-energy x-rays with generating potentials between 10 kV and 50 kV consists of a constant potential generator and two x-ray tubes with either tungsten or molybdenum anode material. Both x-ray tubes have an inherent filtration of 1 mm beryllium. A transmission monitor chamber is used to normalize the x-ray output.

Information on the measuring conditions used for calibration of ionization chambers at NMi and the establishment of Mo/Mo radiation qualities is described in [8].

The characteristics of the radiation beams used for the calibration of the chambers at each laboratory are listed in Table 1.

Table 1. Characteristics of the BIPM, the PTB and the NMi radiation qualities

Institute	BIPM		PTB		NMi	
Anode material	W		Mo		Mo	
Additional filtration	0.06 mm Mo*		0.03 mm Mo		0.03 mm Mo	
Generating potential / kV	HVL / mm Al	$\dot{K}$ / mGy s^{-1}	HVL / mm Al	$\dot{K}$ / mGy s^{-1}	HVL / mm Al	$\dot{K}$ / mGy s^{-1}
20	---	---	0.224	0.55	---	---
23	0.332	1.000	---	---	---	---
25	0.342	1.000	0.282	1.08	0.31	1.00
28	0.356	1.000	0.317	1.07	0.12 **	1.00
30	0.364	1.000	0.337	1.04	0.37	1.80
35	0.388	1.000	0.374	1.07	0.39	1.30
40	0.417	1.000	0.403	1.09	0.41	1.30
50	0.489	1.000	0.440	1.15	---	---
Additional filtration	---		0.03 mm Mo + 2 mm Al		0.03 mm Mo + 2 mm Al	
Generating potential / kV	---	---	HVL / mm Al	$\dot{K}$ / mGy s^{-1}	HVL / mm Al	$\dot{K}$ / mGy s^{-1}
20	---	---	0.450	0.013	---	---
25	---	---	0.580	0.062	---	---
28	---	---	0.633	0.069	0.62	0.07
30	---	---	0.670	0.071	---	---
35	---	---	0.749	0.070	---	---
40	---	---	0.825	0.069	---	---
50	---	---	0.968	0.069	---	---

* 0.423 mm of Be was added to all the qualities for reasons related to the measurement of air attenuation
** without Mo filter in this study

The lower part of Table 1 shows the penetrating beams, with the additional 2 mm Al to simulate the patient exit beam. These qualities have not yet been established at the BIPM.

2.2 Positioning of the ionization chambers

At the BIPM, the reference plane is 500 mm from the exit window of the x-ray tube; at the PTB, the reference distance is 1000 mm and 500 mm from the focus of the Mo and W tubes, respectively; at the NMi, the reference distance is 1000 mm. At all three laboratories, the red line around the Radcal chamber, quoted as 8.5 mm behind the front surface of the chamber body, was placed in the reference plane. The reference plane of the Exradin chamber was taken as 3 mm behind the front surface of the chamber body at the BIPM and at the NMi, whereas at the PTB this plane was taken to be 1.5 mm behind the front surface. Additional measurements were made at the BIPM reproducing this PTB set-up to derive a distance correction factor to enable the comparison of the calibration coefficients measured at each laboratory.

2.3 Reproducibility of the ionization chambers at the BIPM

The two ionization chambers have been calibrated periodically at the BIPM. Repeat calibrations over four years show a standard deviation of 6×10^{-4} in the W/Mo beams. The chambers were calibrated before and after the calibrations performed at the PTB and the NMi and the mean of each pair of calibrations was used for this study; the relative standard uncertainty of these mean values was less than 7×10^{-4}.

3. Additional measurements

The ionization chambers were also calibrated at each institute in one of the reference conditions recommended by the CCRI [6], at a quality common to both NMIs and the BIPM, to take into account any differences in the standards and calibration procedures between the NMI and the BIPM. The characteristics of the quality selected are shown in Table 2.

Table 2. Characteristics of the CCRI reference quality

Radiation quality	25 kV
Generating potential / kV	25
Additional Al filtration / mm	0.372
Al HVL / mm	0.242

4. Uncertainties

The uncertainties associated with the calibration of the ionization chambers at the BIPM, PTB and the NMi are listed in Table 3.

Table 3. Uncertainties associated with the calibration of the ionization chambers at the BIPM, PTB and the NMi

Institute	BIPM	
Uncertainty component	$s^{\dagger} \times 10^2$	$u^{\ddagger} \times 10^2$
air kerma rate $\dot{K}_{\text{std}}$	0.06	0.19
positioning of transfer chamber	0.01	---
ionization current	0.02	0.02
short-term reproducibility	0.05	---
radial non-uniformity	---	0.01
quadratic summation	0.08	0.19
Combined uncertainty of N_K	0.21	

Institute	PTB
Uncertainty component	standard uncertainty
air kerma free in air	0.29
monitor reading during the primary standard measurement	0.05
air density correction of monitor reading during primary standard measurement	0.04
actual distance of PK100	0.01
monitor reading during the secondary standard measurement	0.05
air density correction of monitor reading during secondary standard measurement	0.04
reading of the secondary standard ionization chamber	0.10
actual distance secondary standard chamber	0.01
air density correction for reading of secondary standard chamber	0.04
correction factor for the inhomogeniety of the radiation field in the reference plane	0.06
Combined uncertainty of N_K	0.33

Institute	NMi	
Uncertainty component	$s^{\dagger} \times 10^2$	$u^{\ddagger} \times 10^2$
air kerma rate $\dot{K}_{\text{std}}$	0.07	0.24
positioning of the transfer chamber	---	0.03
ionization current	0.06	0.01
short-term reproducibility	0.10	---
quadratic summation	0.14	0.24
Combined uncertainty of N_K	0.28	

† *s* represents the relative standard uncertainty estimated by statistical methods (type A).
‡ *u* represents the relative standard uncertainty estimated by other means (type B).

5. Results and discussion

The calibration coefficients measured at each institute in the mammography beams, $N_{K,\text{mq}}$, were normalized to the calibration coefficient for the CCRI 25 kV quality, $N_{K,\text{CCRI 25 kV}}$, determined at each laboratory, to remove any differences between the primary standards. The calibration results for each laboratory are plotted as a function of HVL in Figures 1 to 4. Each figure includes the chamber calibration results for the W/Mo beams at the BIPM. The uncertainty bars plotted in the figures represent the combined standard uncertainties, after removing correlations in the $N_{K,\mathrm{mq}}$ and $N_{K,\mathrm{CCRI\ 25\ kV}}$ values for each laboratory.

The results for the Exradin chamber calibrated at the PTB and at the NMi are shown in Fig. 1 and Fig. 2, respectively.

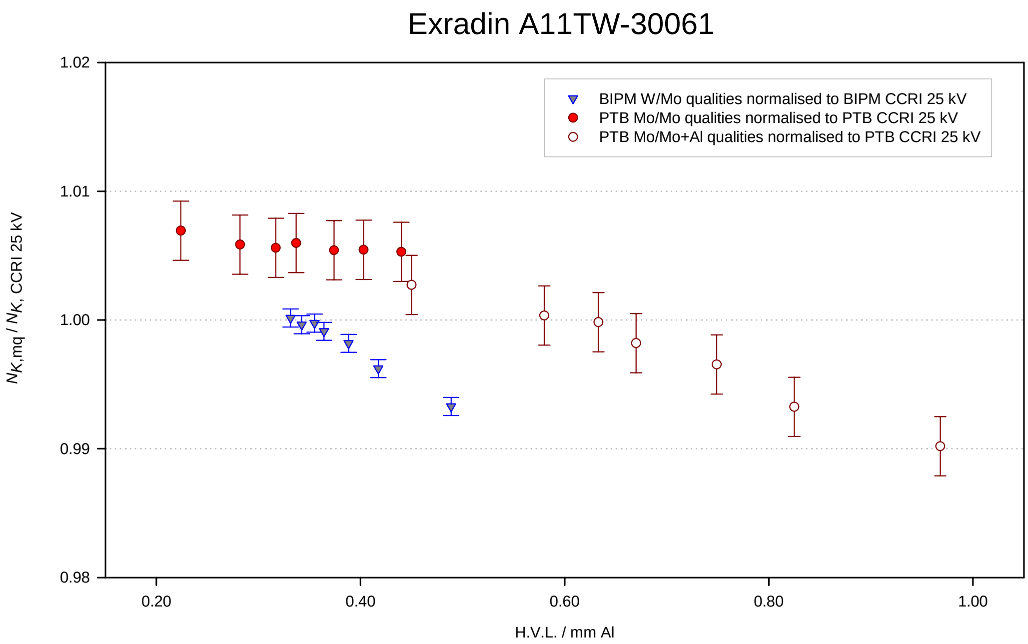

Fig. 1. Normalized calibration coefficients for the Exradin chamber calibrated at the PTB and at the BIPM

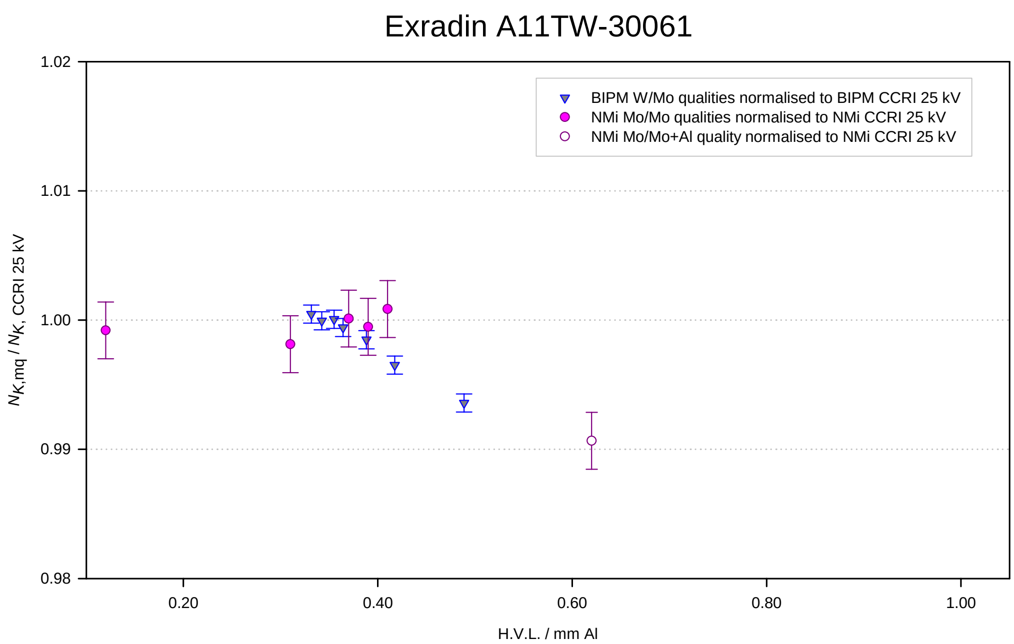

Fig. 2. Normalized calibration coefficients for the Exradin chamber calibrated at the NMi and at the BIPM

The response of the Exradin chamber in the lower HVL range corresponding to the Mo/Mo beams appears to be flatter than the response in the BIPM W/Mo beams. Considering the same HVL range for both types of radiation beams (from 0.3 mm Al to 0.4 mm Al), the calibration coefficients measured at the PTB are constant at the level of 5×10^{-4}, while for the W/Mo beams the chamber shows a slight energy dependence of 4×10^{-3}. The consistency of the calibration performed at the NMi in the Mo/Mo beams is around 4×10^{-3} when the same energy range is considered. For the qualities Mo/(Mo+Al), the HVL values range from 0.45 mm Al to 1.00 mm Al and the energy dependence increases up to 1×10^{-2}.

The PTB and the NMi calibration results for the Radcal chamber are shown in Fig. 3 and Fig. 4, respectively.

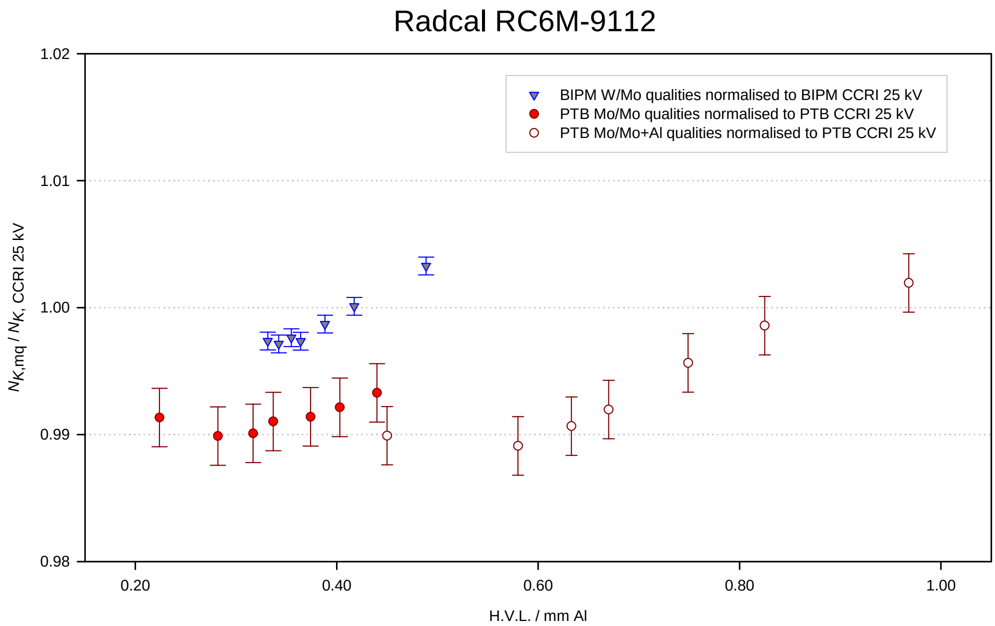

Fig. 3. Normalized calibration coefficients for the Radcal chamber calibrated at the PTB and at the BIPM

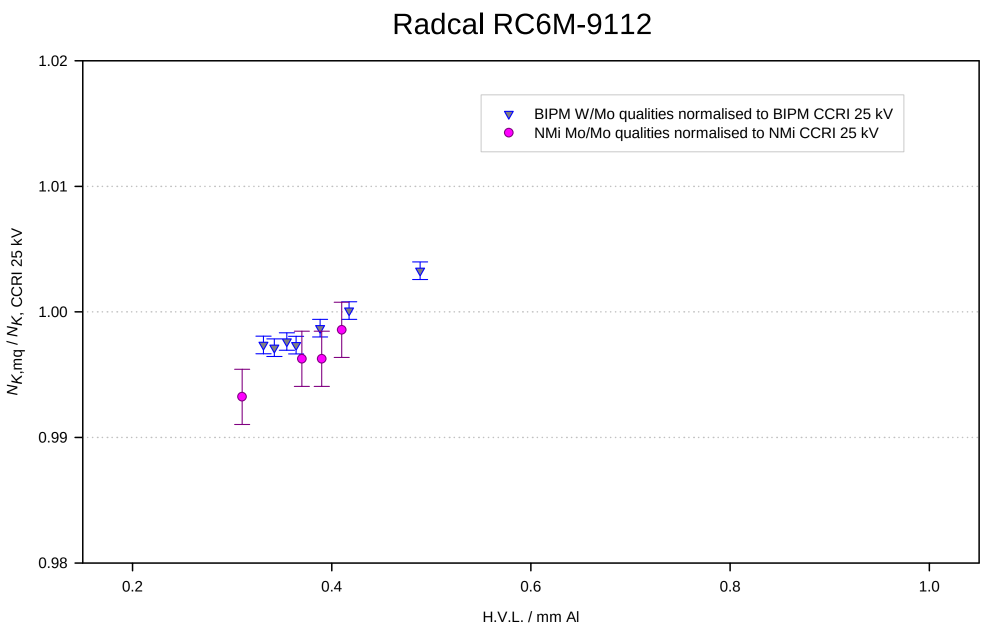

Fig. 4. Normalized calibration coefficients for the Radcal chamber calibrated at the NMi and at the BIPM

The calibration coefficients for this chamber show a similar trend in both types of radiation beams. The energy response of the chamber varies from 6×10^{-3} in the W/Mo beams to 4×10^{-3} in the Mo/Mo beams, increasing to 1.3×10^{-2} when the response to the Mo/(Mo+Al) beams is considered.

The results plotted in Fig. 1 and Fig. 3 corresponding to the calibration of the Exradin and the Radcal, respectively, show not only a dependence on the beam anode material and HVL, but also show a different HVL variation for the two chamber types. The addition of 2 mm Al to the Mo filter, with no significant change of the HVL, causes a change in the chamber response of about 3×10^{-3}.

6. Conclusion

The calibration results for the Exradin A11TW and Radcal R6CM ionization chambers in the simulated mammography beams using a W/Mo anode/filtration combination are in agreement with those obtained in the Mo/Mo beams at the level of 5 to 7 parts in 10^3. Consequently, it would appear that W/Mo beams can be used in the low HVL range to calibrate these two chamber types for subsequent use in Mo/Mo beams. At the higher HVLs using Mo/(Mo+Al) corresponding to patient exit beams, this consistency has not yet been tested at the BIPM.

7. References

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