Rapport BIPM-06/08

Bureau International des Poids et Mesures

Establishment of simulated mammography radiation qualities at the BIPM

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September 2006

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Abstract

New radiation qualities have been established at the BIPM using the tungsten-anode low-energy x-ray tube with molybdenum and rhodium as filters to simulate the radiation beams used in clinical mammography. The evaluation of the correction factors for the primary standard and the measurements of the x-ray spectra are described.

1. Introduction

One of the critical parameters in mammographic procedures is the dose to the breast tissue, which should be kept to a minimum while maintaining adequate diagnostic quality in the recorded image. Accurate dose determinations require measurements performed with radiation measuring instruments calibrated in the x-ray beams used in mammography, traceable to standards laboratories.

Clinical mammography x-ray tubes use a combination of different anode materials (molybdenum or rhodium) and filters (molybdenum, rhodium or paladium). At present, few national standards laboratories are equipped with these x-ray tubes. However, similar radiation qualities can be produced using x-ray tubes with a tungsten-anode and suitable filters. A set of nine such x-ray qualities has been established at the BIPM using the present low-energy x-ray facility.

2. Determination of the beam quality and the air kerma rate

The low-energy x-ray tube has a tungsten-anode with an inherent filtration of 1 mm beryllium. Combinations of the tungsten anode with two filter materials (molybdenum and rhodium) and different tube voltages in the clinical mammography range were used to implement the new radiation qualities, given in Table 1. The determinations of the beam quality, expressed in terms of the half-value layer (HVL), and the air kerma rates were measured with the BIPM low-energy x-ray standard (free-air chamber) [1].

Table 1. Characteristics of the radiation qualities

Radiation quality	M23	M25	M28	M30	M35	M40	M50	R25	R30
Generating potential / kV	23	25	28	30	35	40	50	25	30
Additional filtration	60 µm Mo							50 µm Rh	
HVL / mm Al	0.332	0.342	0.356	0.364	0.388	0.417	0.489	0.464	0.505
μ_{air} / 10^{-3} mm^{-1}	0.213	0.208	0.203	0.198	0.190	0.182	0.166	0.156	0.147

[*] 0.423 mm of Be was added to all the qualities for reasons related to the measurement of air attenuation

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 by bremsstrahlung production in air, and $\Pi\ k_{\mathrm{i}}$ is the product of the correction factors to be applied to the standard, given in Table 2. By a suitable choice of anode current, the air kerma rate was set to 1.00 mGy s^{-1} for all the radiation qualities.

The correction factors for the standard listed in Table 2 were determined by interpolation in terms of HVL from the existing data for the CCRI reference qualities. The factors for the CCRI qualities for electron loss k_{e}, photon scatter k_{sc} and fluorescence k_{fl} were calculated by Burns [2] with Monte Carlo techniques for monoenergetic photons and the results were convoluted using spectral measurements performed with the NMi spectrometer at the BIPM; the correction factor for photon transmission through the aperture edge k_{l} was calculated analytically and the correction for wall transmission k_{p} was measured.

For the present work, these correction factors were recalculated with the Monte Carlo code PENELOPE [3] using a more detailed simulation of the BIPM standard. The results for monoenergetic photons were convoluted with the spectra for the new qualities measured with the BIPM Compton spectrometer (described in section 4).

The air attenuation factor k_{a} was measured for each quality using the method of reduction of the air pressure in a tube placed between the filter and the free-air chamber (the beryllium windows for this tube, of total thickness 0.423 mm, are used as additional filters at all times for all the qualities for consistency).

Table 2. Correction factors for the BIPM standard

Radiation quality	M23	M25	M28	M30	M35	M40	M50	R25	R30
Scattered radiation k_{sc}	0.9974	0.9974	0.9974	0.9974	0.9974	0.9974	0.9975	0.9975	0.9975
Fluorescence k_{fl}	0.9972	0.9972	0.9972	0.9972	0.9973	0.9973	0.9975	0.9974	0.9975
Electron loss k_{e}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Wall transmission k_{p}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Field distortion k_{d}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Aperture edge transmission k_{l}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Air attenuation $k_{\mathrm{a}}^{\dagger}$	1.0218	1.0213	1.0208	1.020	1.0195	1.0187	1.0169	1.0159	1.0150

† Values for 293.15 K and 100.0 kPa; each measurement is corrected using the air density measured at the time.

3. Uncertainties

The uncertainty components associated with the determination of the air kerma rate are listed in Table 3.

Table 3. Estimated relative standard uncertainties in the BIPM determination of air kerma rate for mammography x-ray qualities

		$100\,s_i^{(1)}$	$100\,u_i^{(2)}$
Physical constant			
dry air density (273.15 K, 101 325 Pa)		-	0.01
W/e	/ (J C^{-1})	-	0.15
g		-	0.01
Correction factors			
k_{sc}	scattered radiation	-	0.03
k_{e}	electron loss	-	0.05
k_{fl}	fluorescence	-	0.01
k_{s}	ion recombination	0.01	0.01
k_{pol}	polarity	0.01	-
k_{a}	air attenuation	0.02	0.01
k_{d}	field distortion	-	0.07
k_{l}	transmission through edges of aperture	-	0.01
k_{p}	transmission through walls of standard	0.01	-
k_{h}	humidity	-	0.03
Measurement of $I/v\rho$			
v	volume /cm^3	0.03	0.05
I	ionization current correction concerning ρ (temperature, pressure, air compressibility)	0.02	0.02
	positioning of standard	0.01	0.01
Relative standard uncertainty in $\dot{K}_{\mathrm{BIPM}}$			
quadratic sum		0.05	0.19
combined uncertainty		0.20	

(1) s_i represents the relative standard Type A uncertainty, estimated by statistical methods;
(2) u_i represents the relative standard Type B uncertainty, estimated by other means.

4. Determination of spectra

4.1 Measurement of spectra

An accurate knowledge of each spectrum is required to evaluate the energy-dependent correction factors involved in the air kerma determination. One of the problems in determining the spectra is the high flux of the x-ray beams. While several techniques exist to solve this problem, the Compton scattering method, which consists of placing a scattering material in the primary beam, measuring the scattered photons at a certain angle and then reconstructing the primary beam, was chosen for the present work.

A commercial Compton spectrometer was used that consists of a scattering chamber with lead walls, lead collimators and a PMMA rod of circular cross section used as the scatterer (Fig. 1). The scattered photons were detected at 90° with a low-energy pure germanium detector (LEGe) coupled to a multichannel analyser (MCA). The calibration of the MCA was performed using the known energies of the x- and γ-rays emitted by radioactive sources of ^{125}I and ^{241}Am.

The primary x-ray spectra were reconstructed from the resulting pulse height distribution using commercial software [4].

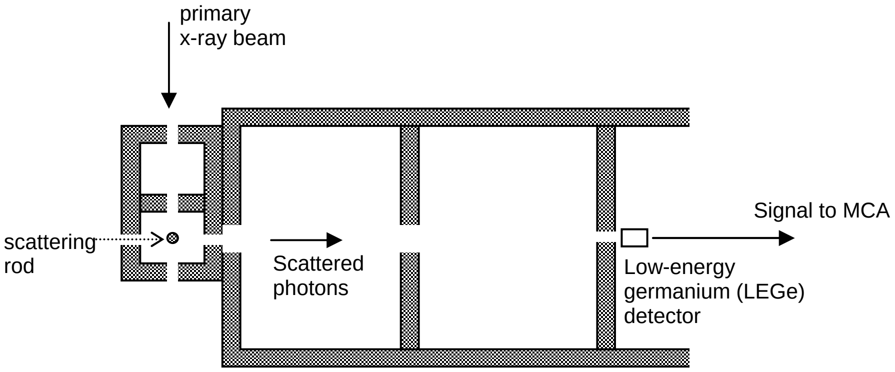

Fig. 1. Schematic diagram of the Compton spectrometer

4.2 Simulation of the spectra

The mammography spectra were also obtained by simulation with Monte Carlo techniques using the PENELOPE code [3]. The x-ray tube configuration (target, filters and collimation) has been simulated with the PENELOPE geometry code PENGEOM, as shown in Fig. 2.

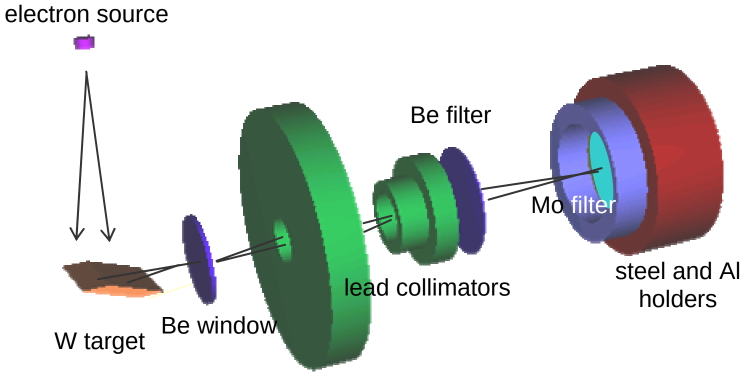

Fig. 2. Model of the x-ray tube, filters and collimators

In the first step, this model was used to create a phase-space file of photons crossing the first lead collimator (plane at 5 cm from the centre of the target), including the energy, angle and position of each particle. The photon and electron cut-off energies were set to 1 keV. The following values were chosen for the electron transport parameters in PENELOPE[1]:
C1 = C2 = 0.2, Wcc = Wcr = 1 keV. Interaction forcing for bremsstrahlung emission was

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[1] C1 and C2 determine the cutoff angle that separates hard from soft elastic interactions; Wcc and Wcr are the cutoff energies for the production of hard inelastic and bremsstrahlung events, respectively.

applied to the primary electrons. This phase-space file was used as input for the transport of photons through the collimators and filters; the distribution of the photon number with energy was generated at 50 cm from the centre of the target. For the second step, the photon cut-off energy was also set to 1 keV, while the electron transport cut-off was raised to the maximum photon energy value (that is, no electron transport).

5. Results

5.1 Spectral measurements

The measured spectra corresponding to 23 kV, 30 kV, 50 kV with the Mo filter and 30 kV with the Rh filter are shown in Fig. 3. The energy bins are 0.2 keV. No correction was made for the production of x-ray fluorescence in the LEGe detector.

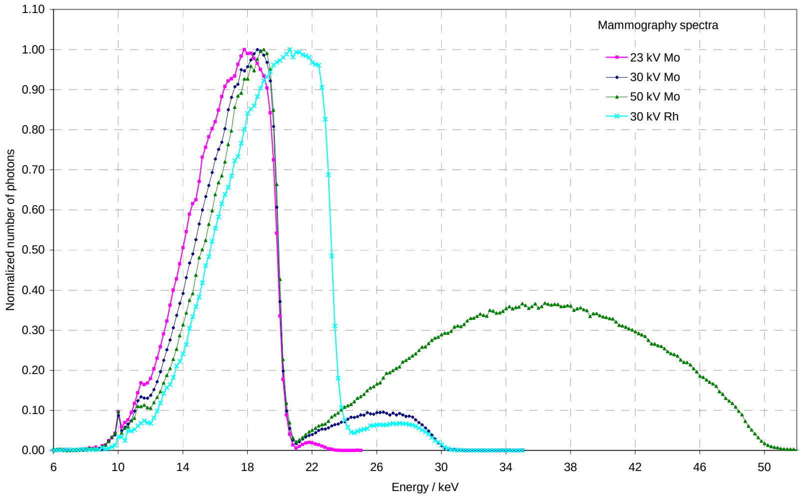

Fig. 3. Spectra measured with the Compton spectrometer

5.2 Spectral simulations

Figures 4 and 5 show the spectra for the 30 kV qualities with Mo and Rh filters, respectively, simulated with the PENELOPE code. Each spectrum is compared with that measured using the Compton spectrometer.

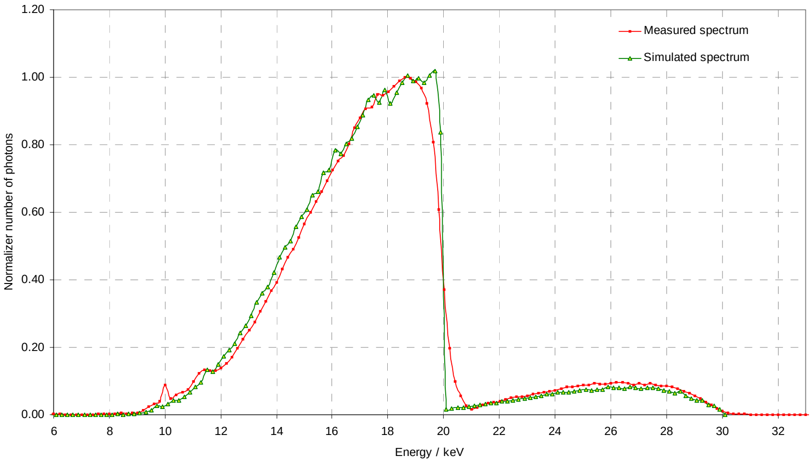

Fig. 4. Comparison of the simulated and measured spectra for the 30 kV, Mo filter quality

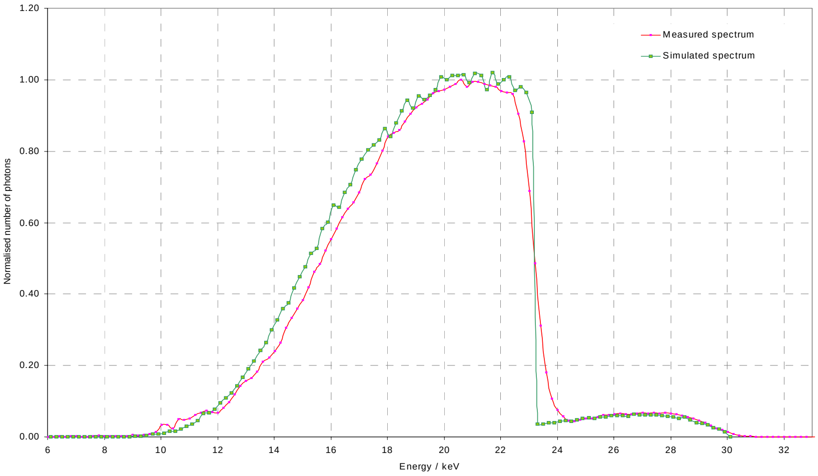

Fig. 5. Comparison of the simulated and measured spectra for the 30 kV, Rh filter quality

6. Discussion and Conclusions

The correction factors used for the primary air kerma determination were derived by interpolation in terms of the HVL from the correction factors calculated for the CCRI qualities. The subsequent recalculation of these factors using the measured Mo and Rh spectra and an improved model of the standard showed the factors to be insensitive at the 3×10^{-4} level.

The measured and calculated spectra for the 30 kV, Mo filter quality show slightly better agreement than those for the Rh filter qualities, although the maximum deviation between the curves in the latter case remains less than 0.35 keV. This deviation might be due to statistical fluctuations, which could be improved with further calculations. The energy broadening observed in the measured spectra at the absorption edge of the two filters may arise from the energy resolution of the Compton spectrometer. However, these differences have no significant effect in the calculation of the standard correction factors.

The suitability of these simulated mammography x-ray qualities for the calibration of ionization chambers currently used in mammography is under investigation. For this separate study, the response of two different ionization chamber types calibrated in these beams is compared with that obtained from calibration in various mammography beams [5].

7. References

[1] Boutillon M., Henry W.H. and Lamperti P.J., Comparison of exposure standards in the 10-50 kV x-ray region, *Metrologia*, 1969, **5**, 1-11.

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[3] Salvat, F., Fernandez-Varea, J.M., Acosta, E., Sempau, J., Penelope – A Code System for Monte Carlo Simulation of Electron and Photon Transport, NEA/NSC/DOC(2001)19 (ISBN 92-64-18475-9).

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