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Establishment of reference radiation qualities for mammography

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Abstract

An x-ray tube with a molybdenum anode was installed at the BIPM during 2009. Four radiation qualities were established as reference beams for mammography comparisons and calibrations in accordance with the request of the CCRI. A new primary standard for air kerma was constructed at the BIPM to be used for the dosimetry of these beams, and also to serve as a replacement in the event of a failure of the existing standard for the tungsten-anode CCRI radiation qualities. Details of the standard's construction, the calculated corrections and the measurements are presented.

1. Introduction

Mammography in many Member States of the BIPM is subject to legislation in relation to the mean glandular tissue dose that is acceptable, particularly for well-woman screening programmes. Consequently, in 2001, the CCRI requested that the BIPM study the needs of the NMIs and how these should be addressed. The BIPM began this work in 2001 by studying the simulation of mammography beams using a molybdenum filter with the existing tungsten anode x-ray tube. It became clear that to meet the needs of the NMIs for comparisons in this domain and to provide SI traceable calibrations, the BIPM should establish reference radiation qualities for mammography x-ray beams. First, a study of the response of ionization chambers to mammography beams was made. Then a new primary standard was designed and constructed at the BIPM to be used for the dosimetry of these beams, and also to serve as a replacement in the event of a failure of the existing standard for the tungsten-anode CCRI radiation qualities. Finally, a molybdenum anode x-ray tube was installed at the BIPM during 2009. In accordance with the request of the NMIs through the CCRI, four radiation qualities have been established as reference beams for mammography comparisons and calibrations.

2. New primary standard for mammography

2.1 Design of the standard

The new primary standard is a parallel-plate free-air chamber, identified as FAC-L-02. It has been designed to be used for x-ray beams operating up to 50 kV and to minimize the correction factors involved in the air-kerma determination [1]. A schematic diagram of the chamber is shown in Figure 1.

The separation between the high-voltage plate and the collector is 70 mm, just sufficient to reduce electron loss to a negligible amount for the CCRI 50 kV(a) tungsten-anode quality.

A coordinate measuring machine (CMM) was used for the measurements of the critical dimensions of the aperture and collector and to assure the co-planarity of the collector and the guard plate. The collector support was designed to allow the co-planarity to be adjusted with a tolerance of around 5 µm.

The collector and the guard plate are of aluminium with a thin graphite coating; the collector is placed in the centre of the guard plate surrounded by an air gap of 0.5 mm. As is normal for a chamber of this type, the effective collector length (15.537(2) mm) includes half of the front and rear air gaps.
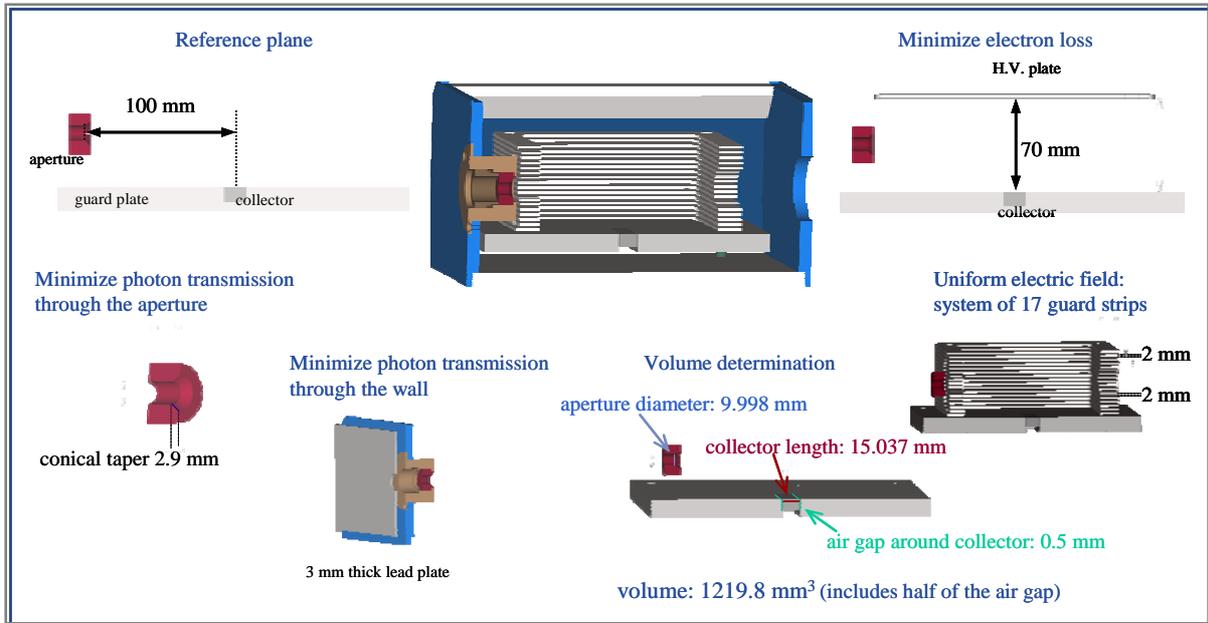

Fig.1. The new free-air chamber, FAC-L-02. A schematic representation (not to scale) showing the various components and important dimensions.

A system of 17 guard strips, uniformly spaced between the ground and high-voltage plates and parallel to them, surrounds the air cavity in order to produce a uniform electric field in the collecting region. The individual strips are 20 mm wide and 2 mm thick and are spaced by gaps of 2 mm.

A tungsten-alloy diaphragm 13.04 mm thick with an aperture 9.998(1) mm in diameter defines the reference plane at 100.2 mm from the centre of the collecting region. In order to reduce photon transmission, the innermost 2.9 mm forms a conical section that increases the diameter to 15.8 mm. The effective aperture length is therefore 10.14 mm.

The collecting volume defined by the aperture diameter and the collector length is 1219.8(4) mm^3.

The air temperature inside the chamber is measured using a thermistor placed just above the high-voltage plate. This position was chosen after studying the temperature distribution within the chamber and measurements at this location best represent the temperature of the collecting air volume.

A 3 mm thick lead plate with an aperture window was added to the front wall to minimize photon transmission through the aluminium wall.

2.2 Correction factors

Many of the correction factors for the standard involved in the determination of K_{air} (see section 3.4), namely, those for electron loss, photon scatter and fluorescence inside the chamber, bremsstrahlung production, photon transmission through the diaphragm edge, photon scatter and fluorescence from the diaphragm, photon scatter from the diaphragm holder and front wall transmission, were calculated using the Monte Carlo code PENELOPE [2], for mono-energetic photons from 2 keV to 50 keV in steps of 2 keV. A detailed simulation of the new BIPM standard was performed using the PENELOPE geometry package PENGEOM, as shown in Figure 2.
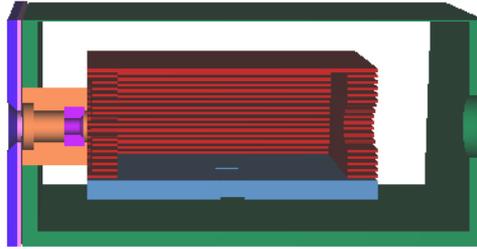
Fig.2. A cut-away of the geometry used for Monte Carlo
simulations, created using the PENGEOM code of PENELOPE [2].

The results for mono-energetic photons were folded with measured and simulated spectra for the BIPM reference qualities (see section 4). The results of these calculations are in close agreement with similar calculations for the existing standard [3].

The correction factor for the lack of saturation due to ion recombination and diffusion was determined following the method proposed by De Almeida and Niatel [4] as detailed by Boutillon [5]. The correction factor for air attenuation within the chamber was measured using the same method (reduced air pressure pipe) employed in the existing standard for the tungsten-anode qualities [1].

2.3 Comparison with the existing standard

The new standard has been compared with the existing primary standard, FAC-L-01, for the tungsten-anode x-ray tube at the CCRI reference qualities. Initial discrepancies of the order of 4 parts in 10^3 motivated a series of studies. These included a study of the volume determination by changing the collector length and the air gap between the collector and the guard plate; a study of contact potentials between the collector and the guard plate by applying a few volts to the guard plate while maintaining the collector at ground potential; and a study of the temperature measurement and its stability inside the chamber by adding a second thermistor in the centre of the collecting air volume.

None of the experiments performed could explain the initial discrepancy, which increased to as much as 8 parts in 10^3 during some of these measurements. When the chamber was first constructed and each time that it was dismantled and reassembled, the planarity of the collector-guard plate was checked using the CMM and a tolerance of 50 µm was accepted. To examine this choice, the upstream edge of the collector was raised and lowered by around 100 µm with respect of the guard plate. This resulted in discrepancies of up to 3 parts in 10^2, indicating that the tolerance of 50 µm was too high and might explain the fluctuating results. A new collector support was designed, allowing the collector to be adjusted to better than 5 µm with respect to the guard plate. The collector and guard plate, both of aluminium, were cleaned and mounted again with the new support. With this configuration, the discrepancy

between the standards was reduced to 1 part in 10^3, but it was not stable, increasing to 4 parts in 10^3 three months later with no change in the co-planarity. Finally, once the collector and guard plate were coated with graphite the discrepancy was reduced again to 1 part in 10^3 and has since remained constant. It is also notable that the polarity effect, previously measured consistently as 1.5 parts in 10^3, was reduced to below 1 part in 10^4 following the graphite coating.

3. Establishing new radiation beams: determination of the beam quality and the air-kerma rate

3.1 BIPM irradiation facility

The Mo-anode x-ray tube has been installed in the low-energy x-ray laboratory at the BIPM, sharing the facilities with the W-anode x-ray tube. The existing high-voltage generator, voltage stabilization and anode current measuring system are used for both tubes. A new cooling system was installed and also serves both x-ray tubes. The Mo-anode tube specification is given in Table 1.

Table 1. Main characteristics of the Mo-anode x-ray tube

Tube MXR-101 Mo COMET	
Nominal x-ray tube voltage	100 kV
Max. tube current at nominal voltage	10 mA
Power	1 kW
Inherent filtration (window)	0.8 mm Be
Target angle	40°
Focal spot diameter	5.5 mm

The existing calibration bench was used to support the Mo-anode tube (with the radiation beam projected in the opposite direction to that generated by the W-anode tube) and a high-precision translation table connected to a motion control device. The tube remains in a fixed position while the translation table enables the alternate positioning on the beam axis of the standard and an instrument for comparison or calibration. The reference plane is 600 mm from the tube centre.

Radiographic films were used for the study of the radiation field (size, shape and orientation). Horizontal and vertical radial profiles were measured using a thimble ionization chamber. Using the data from the radial profiles and the radiographic images, a system of two lead collimators was designed and machined in order to produce a field 10 cm in diameter at the reference plane.

3.2 New radiation qualities

Four radiation qualities, chosen by participants of the CCRI(I) and similar to those used in other standards laboratories for dosimetry in mammography, were set up as reference beams for comparisons and calibrations. The characteristics of the beams are given in Table 2. The beam quality, expressed in terms of the aluminium half-value layer (HVL), was determined

for each beam using the new primary standard. The anode current for each quality was chosen to give an air-kerma rate of 2 mGy s^{-1} in the reference plane.

Table 2. Characteristics of the radiation qualities for mammography

Beam parameter	Radiation quality			
	Mo25	Mo28	Mo30	Mo35
Generating potential / kV	25	28	30	35
Additional filtration	30 µm Mo			
Al HVL / mm	0.277	0.310	0.329	0.365
$(\bar{\mu}/\rho)/\text{cm}^2\,\text{g}^{-1}$	2.20	1.99	1.91	1.74

3.3 Measurement and simulation of energy spectra

The photon energy spectra were measured using the Compton scattering method, described in [6]. The scattered photons were detected at 90° with a low-energy pure germanium detector (LEGe) coupled to a multichannel analyser (MCA). The energy 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 [7].

The mammography spectra corresponding to the qualities Mo25 and Mo30 were also obtained by simulation with Monte Carlo techniques using the code PENELOPE. The x-ray tube configuration (Mo target, Mo filter and collimation) was simulated using the PENELOPE geometry code PENGEOM. Details of the simulation of the spectra can be found in [6].

The spectrum corresponding to 30 kV measured with the Compton spectrometer is shown in Figure 3, together with that calculated using the PENELOPE code.
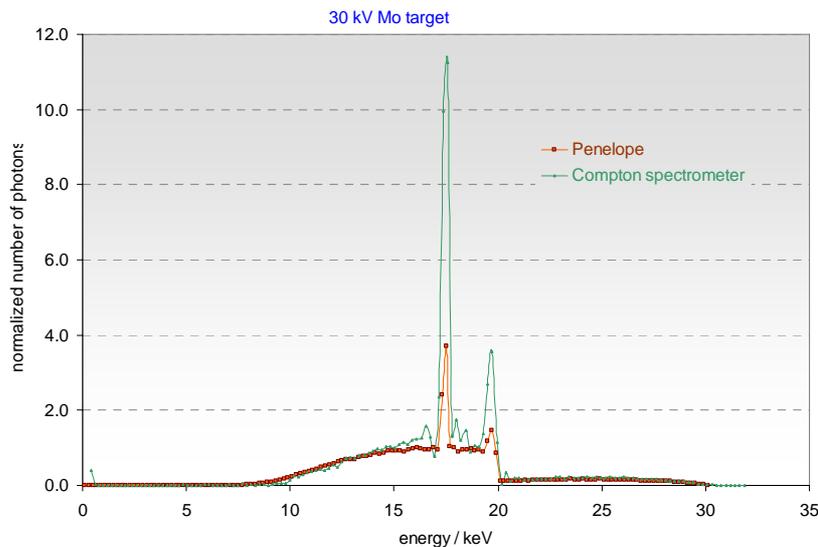

Figure 3. Comparison of the simulated and measured spectra for the Mo30 quality

3.4 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

$$\dot{K} = \frac{I}{\rho_{air}V} \frac{W_{air}}{e} \frac{1}{1-g_{air}} \prod_i k_i \qquad (1)$$

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

The correction factors for the standard involved in the determination of K_{air} were either measured or calculated using Monte Carlo techniques. The results calculated for mono-energetic photons were convoluted with the spectra measured with the BIPM Compton spectrometer. The results are shown in Table 3. These factors were also evaluated using the simulated spectra for the qualities Mo25 and Mo30; despite evident differences in the spectra around the characteristic peaks of Mo (Figure 3), the correction factors for the standard were determined to be insensitive to these differences. The diaphragm correction factor k_{dia} is the combined effect of photon transmitted through the diaphragm and scattering and fluorescence photons produced in the diaphragm.

Table 3. Correction factors for the BIPM standard

Correction factor	Radiation quality			
	Mo25	Mo28	Mo30	Mo35
Scattered radiation k_{sc}	0.9977	0.9977	0.9978	0.9978
Fluorescence k_{fl}	0.9975	0.9976	0.9976	0.9977
Electron loss k_e	1.0000	1.0000	1.0000	1.0000
Saturation k_s	1.0015	1.0015	1.0015	1.0015
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000
Air attenuation k_a [1]	1.0269	1.0244	1.0233	1.0212
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000
Field distortion k_d	1.0000	1.0000	1.0000	1.0000
Diaphragm correction k_{dia}	0.9996	0.9995	0.9995	0.9995

[1] Values at 293.15 K and 101.325 kPa for an attenuation length of 10.0 cm.

The uncertainties in the determination of the air-kerma rate are listed in Table 4.

4.   Calibration of transfer standards

A series of 3 transfer standards has been calibrated against the new primary standard in the newly established mammography reference beams. The reproducibility of the calibration coefficients is better than 3 parts in 10^4, based on the 4 sets of measurements made to date.

5.   Conclusion

The BIPM has now established the new primary standard and the four reference beam qualities proposed by the CCRI for mammography comparisons and calibrations. Consequently, the BIPM is now prepared to undertake these dosimetry comparisons for mammography metrology as requested by the CCRI.

Table 4. Estimated relative standard uncertainties in the BIPM determination of air-kerma rate for mammography x-ray qualities

Symbol	Parameter / unit	Relative standard uncertainty [1]	
		s_i	u_i
Physical constants			
ρ_a	dry air density (0°C, 101.325 kPa) / kg m^{-3}	–	0.01
W/e	mean energy per charge / J C^{-1}	–	0.15
g	fraction of energy lost in radiative processes	–	0.01
Correction factors			
k_{sc}	scattered radiation	–	0.03
k_{fl}	fluorescence	–	0.05
k_e	electron loss	–	0.01
k_s	saturation	0.01	0.01
k_{pol}	polarity	0.01	–
k_a	air attenuation	0.02	0.01
k_d	field distortion	–	0.07
k_{dia}	diaphragm	–	0.03
k_p	wall transmission	0.01	–
k_h	humidity	–	0.03
Measurement of I/υ			
I	ionization current (T, P, air compressibility)	0.02	0.02
υ	volume	0.03	0.05
	positioning of standard	0.01	0.01
Combined uncertainty of the BIPM determination of air-kerma rate			
quadratic summation		0.05	0.19
combined relative standard 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.

References

[1] Burns D.T., Büermann L., 2009, Free-air ionization chambers, *Metrologia,* 2009, **46(2),** S9-S23

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

[3] Burns DT, 2003, New correction factors for the BIPM free-air chamber standards. CCRI(I)/03-28 .

[4] De Almeida CE, Niatel MT, 1986, Comparison between IRD and BIPM exposure and air kerma standards for cobalt gamma rays. *Rapport* BIPM-1986/12 (Sèvres: Bureau International des Poids et Mesures).

[5] Boutillon M., 1998, Volume recombination parameter in ionization chambers, *Phys. Med. Biol.,* 1998, **43**, 2061-2072

[6] Kessler C, 2006, Establishment of simulated mammography radiation qualities at the BIPM, *Rapport BIPM-*2006/08 8 pp.

[7] Matscheko G, Ribberfors R, 1989, A generalised algorithm for spectral reconstruction in Compton spectroscopy with corrections for coherent scattering, *Phys. Med. Biol.* **34** (1989) 835-841.