APPENDIX TO IAEA CALIBRATION CERTIFICATE

CALIBRATION OF REFERENCE DOSIMETERS FOR DIAGNOSTIC RADIOLOGY AT THE IAEA DOSIMETRY LABORATORY

1 INTRODUCTION

Reference dosimeters are calibrated for diagnostic and interventional radiology beams at the IAEA Dosimetry Laboratory (DOL) according to procedures described in the IAEA TRS-457 [1] and in the Chapter 21 of the IAEA Diagnostic Radiology Physics Handbook [2]. The calibrations are performed by the substitution method using a monitor chamber for normalization of the X-ray beam output. The IAEA reference standard ionization chambers and current source used for these calibrations are calibrated at the BIPM or other Primary Standard Laboratories every 3 years.

The International Commission on Radiation Units and Measurements (ICRU) published the Report 90 *"Key Data for Ionizing-Radiation Dosimetry: Measurement Standards and Applications"* in October 2016 [3]. This report recommends revised values and uncertainties for some physical data required for realization of air kerma, reference air kerma and absorbed dose to water quantities of photon radiation by primary measurement standards. Details of these changes were published in 2018 [4]. The IAEA's dosimetry standards are traceable to BIPM and PTB. The change to the IAEA standards were implemented for all calibrations performed after 1st of January 2019. The implementation was done either through a new calibration of the IAEA standard or using values given in the notification letter [5].

2 CALIBRATION PROCEDURES

Calibrations are either made for a system, composed of an ionization chamber plus an electrometer (hence system calibration), or for an ionization chamber only (component calibration). For calibration of the ionization chamber only, the ionization currents are measured with the IAEA electrometers. For system calibrations, the internal bias supply in the user electrometer/dosimeter is used for the polarizing voltage. No correction for the measured ionization currents due to ion recombination is applied.

The air kerma calibration coefficient N_K [mGy/scale unit] of the dosimeter under calibration is determined as the ratio of the air kerma rate $\dot{K}_{air}$ [mGy/s] obtained with the IAEA reference standard, and the reading $\dot{M}$ [scale units/s] of the dosimeter corrected for the reference conditions.

2.1 Reference conditions

The reference point of the ionization chamber, where the calibration coefficients apply, is considered to be in the geometrical centre of the collecting volume as defined by the external walls (unless another indication is given). Details on the geometrical centre for each specific chamber are given in the operation manual of the ionization chambers. If the chamber stem has a mark, this mark is oriented towards the radiation source during the calibration.

The calibration coefficients refer to air temperature T = 20°C, air pressure P = 101.325 kPa and 50% relative air humidity. The ambient conditions (temperature, pressure and humidity), prevailing at the DOL during the calibrations, are monitored continuously. Typically, the temperature in the laboratory is within 20°C - 24°C with fluctuations less than 0.5°C. The measured ionization current, I [nA] is corrected for the reference temperature 20°C and pressure 101.325 kPa. The relative air humidity at the dosimetry laboratory is kept between 30% and 70%. No correction is applied for the humidity.

2.2 CALIBRATIONS IN TERMS OF AIR KERMA

2.2.1 X-ray beam set-up

The chamber is positioned free in air, so that its reference point is on the central axis of the beam. The chamber is mounted vertically and held by the stem. In the case of plane-parallel chamber the entrance surface is perpendicular to the central axis of the beam. In the case of cylindrical chamber its long axis is perpendicular to the central axis of the beam. The distance from the focus of the X-ray tube to the reference point of the chamber, FCD, is 1 m. The size of the radiation field (50% and 99% isodose levels) at the reference plane are ∅ 10 cm and ∅ 8 cm respectively. FIG. 1 shows the set-up.

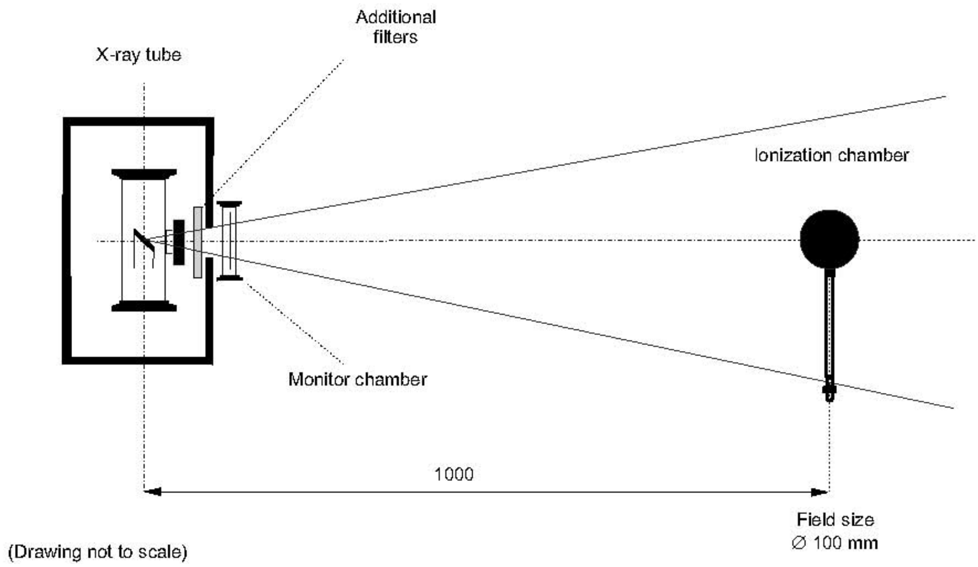

FIG. 1. Set-up for calibration in terms of air kerma for diagnostic radiology X-ray beams

2.2.2 Radiation qualities

The characteristics of the diagnostic radiology X-ray radiation qualities used for calibration are given in Tables I below. The applied air kerma rate is approximately 40 mGy/min for the non-attenuated radiation qualities (Tables I, III, IV, VI, VII, VIII, IX and X) and 3 mGy/min for the attenuated radiation qualities (Tables II and V).

TABLE I: RQR X-ray radiation qualities (tungsten anode) [6]

Radiation quality	Tube voltage [kV]	Added filtration[a] [mm Al]	1st HVL [mm Al]
RQR 2	40	2.40	1.42
RQR 3	50	2.40	1.78
RQR 4	60	2.74	2.18
RQR 5[b]	**70**	**2.94**	**2.57**
RQR 6	80	3.09	3.00
RQR 7	90	3.32	3.58
RQR 8	100	3.47	4.02
RQR 9	120	3.90	5.04
RQR 10	150	4.72	6.71

[a] Inherent filtration 1 mm Be;
[b] Reference radiation quality in the series

TABLE II: RQA X-ray radiation qualities (tungsten anode) [6]

Radiation quality	Tube voltage [kV]	Added filtration[a] [mm Al]	1st HVL [mm Al]
RQA 2	40	6.5	2.21
RQA 3	50	12.6	3.77
RQA 4	60	19.0	5.38
RQA 5[b]	**70**	**24.3**	**6.89**
RQA 6	80	29.3	8.24
RQA 7	90	33.4	9.26
RQA 8	100	37.6	10.24
RQA 9	120	44.1	11.64
RQA 10	150	49.9	13.40

[a] Inherent filtration 1 mm Be
[b] Reference radiation quality in the series

TABLE III: RQT X-ray radiation qualities (tungsten anode) [6]

Radiation quality	Tube voltage [kV]	Added filtration[a]	1st HVL [mm Al]
RQT 8	100	3.48 mm Al + 0.20 mm Cu	7.02
RQT 9[b]	**120**	**3.88 mm Al + 0.25 mm Cu**	**8.47**
RQT 10	150	4.70 mmAl + 0.30 mm Cu	10.26

[a] Inherent filtration 1 mm Be
[b] Reference radiation quality in the series

TABLE IV: RQR-M X-ray radiation qualities with molybdenum anode [6]

Radiation quality	Tube voltage [kV]	Added filtration[a] [mm Mo]	1st HVL [mm Al]
Mo+Mo 25	25	0.033	0.28
Mo+Mo 28[b]	**28**	**0.033**	0.32
Mo+Mo 30	30	0.033	0.34
Mo+Mo 35	35	0.033	0.37

[a] Inherent filtration 1 mm Be
[b] Reference radiation quality in the series

TABLE V: RQA-M X-ray radiation qualities with molybdenum anode [6]

Radiation quality	Tube voltage [kV]	Added filtration[a] [mm Al]	1st HVL [mm Al]
Mo+Mo+Al 25	25	Mo+Mo 25 + 2.0	0.57
Mo+Mo+Al 28[b]	**28**	Mo+Mo 28 + 2.0	0.62
Mo+Mo+Al 30	30	Mo+Mo 30 + 2.0	0.65
Mo+Mo+Al 35	35	Mo+Mo 35 + 2.0	0.72

[a] Inherent filtration 1 mm Be
[b] Reference radiation quality in the series

TABLE VI: Mo+Rh X-ray radiation qualities with molybdenum anode

Radiation quality	**Tube voltage [kV]**	**Added filtration[a] [mm Rh]**	**1st HVL [mm Al]**
Mo+Rh 25	25	0.0285	0.35
Mo+Rh 28[b]	**28**	0.0285	0.39
Mo+Rh 30	30	0.0285	0.41
Mo+Rh 35	35	0.0285	0.44

[a] Inherent filtration 1 mm Be
[b] Reference radiation quality in the series

TABLE VII: W+Mo X-ray radiation qualities (tungsten anode)

Radiation quality	**Tube voltage [kV]**	**Added filtration[a] [mm Mo]**	**1st HVL [mm Al]**
W+Mo 25	25	0.066	0.34
W+Mo 28[b]	**28**	**0.066**	0.36
W+Mo 30	30	0.066	0.36
W+Mo 35	35	0.066	0.39

[a] Inherent filtration 1 mm Be
[b] Reference radiation quality in the series

TABLE VIII: W+Al X-ray radiation qualities (tungsten anode)

Radiation quality	**Tube voltage [kV]**	**Added filtration[a] [mm Al]**	**1st HVL [mm Al]**
W+Al 25	25	0.513	0.32
W+Al 28[b]	**28**	**0.513**	0.36
W+Al 30	30	0.513	0.39
W+Al 35	35	0.513	0.44

[a] Inherent filtration 1 mm Be
[b] Reference radiation quality in the series

TABLE IX: W+Rh X-ray beam qualities (tungsten anode)

Radiation quality	**Tube voltage [kV]**	**Added filtration[a] [mm Rh]**	**1st HVL [mm Al]**
W+Rh 25	25	0.0477	0.46
W+Rh 28[b]	**28**	**0.0477**	0.49
W+Rh 30	30	0.0477	0.50
W+Rh 35	35	0.0477	0.54

[a] Inherent filtration 1 mm Be
[b] Reference radiation quality in the series

TABLE X: W+Ag X-ray beam qualities (tungsten anode)

Radiation quality	Tube voltage [kV]	Added filtration[a] [mm Ag]	1^{st} HVL [mm Al]
W+Ag 25	25	0.0492	0.47
W+Ag 28 [b]	**28**	**0.0492**	0.52
W+Ag 30	30	0.0492	0.54
W+Ag 35	35	0.0492	0.59

[a] Inherent filtration 1 mm Be

[b] Reference radiation quality in the series

3 USE OF CALIBRATION COEFFICIENTS

The reference instruments calibrated at the DOL can be used, in another radiation beam, to determine the beam output rate (air kerma), subject to the provisions listed below:

- The humidity conditions should not differ significantly from those prevailing at the IAEA Dosimetry Laboratory. If the relative humidity is outside the range of 30% - 70%, corrections based on [7] should be made.
- If the conditions of measurement differ significantly from those at DOL, additional corrections or uncertainty for the differences may be needed. In particular when they are related to:
    - the radiation quality (different HVL and/or photon spectrum), e.g. related uncertainties for mammography can be found in [8];
    - the radial non-uniformity of the beam over the cross section of the ionization chamber;
    - the dose rate and pulse rate. It should be noted that the calibration coefficients determined at the DOL are not corrected for the recombination. Additional information on this effect can be found in [1] and [9].
    - the applied polarity and scale used during the calibration at the DOL reported in the calibration certificate. If the instrument is used with a different polarity or scale from those listed in the calibration certificate, the user is advised to determine the effect of these differences and decide on their effects on the measurements. Additional information on these effects and ways to correct for them can be found in [1].

4 CALIBRATION UNCERTAINTIES

The methodology for estimating the uncertainties of calibrations at the IAEA Dosimetry Laboratory is based on the JCGM [10] and IAEA [11] guides on uncertainty. All sources of uncertainty are identified and classified as Type A or Type B, as per JCGM classification.

The uncertainty associated to the IAEA calibrations is a relative combined standard uncertainty, with a coverage factor of k = 2, which for a normal distribution corresponds to a level of confidence of approximately 95%.

The contributions to the total relative uncertainty in the calibration coefficient are determined in 2 steps:

1. uncertainties arising from measurements made by the IAEA reference instrument to determine the reference air kerma rate in the radiation beams where the user's instrument will be calibrated, and
2. uncertainties related to the instruments to be calibrated (user's instrument). Instruments calibrated at the IAEA are usually reference class instruments. Typical uncertainties are assumed for these instruments.

These two components are further divided into sub-components and their classification (Type A or Type B) is determined. Uncertainty budgets of IAEA calibrations are given in Tables XI-XII.

TABLE XI: Estimated relative standard uncertainty in the IAEA calibration.
RQR, RQA and RQT X-ray beams: Air kerma rate.
(IAEA CMCs Identifiers in the BIPM KCDB): EUR-RAD-IAEA 1020-1024)

Uncertainty component	*Uncertainty (%)*	
	Type A	Type B
Step 1: Reference standard		
Calibration from BIPM/PSDL		0.50
Long term stability of the secondary standard		0.25
Spectral difference PSDL/IAEA		0.06
Current measurement - Ref. Std.	0.05	0.10
Temperature and pressure correction - Ref. Std.		0.05
Current measurement - Monitor	0.05	0.10
Temperature and pressure correction - Monitor		0.05
Relative combined standard uncertainty in Step 1	*0.07*	*0.58*
Step 2: Instrument to be calibrated		
Current measurement - User Chamber	0.06	0.20
Temperature and pressure correction - User Chamber		0.05
Current measurement - Monitor	0.05	0.10
Temperature and pressure correction - Monitor		0.05
Stability of the monitor chamber		0.09
Difference in radial non-uniformity of the beam		0.17
Chamber positioning		0.01
Relative combined standard uncertainty in Step 2	*0.08*	*0.30*
Relative combined standard uncertainty (Steps 1 + 2)	*0.11*	*0.66*
Standard combined uncertainty (k = 1)	*0.67*	
Relative expanded uncertainty (*k* = 2)	**1.3**	

TABLE XII: Estimated relative standard uncertainty in the IAEA calibration.
Mo+Mo+Al, Mo+Mo*, Mo+Rh, W+Mo*, W+Al, W+Rh and W+Ag mammography X-ray beams: Air kerma rate.

(IAEA CMCs Identifier in the BIPM KCDB): EUR-RAD-IAEA 1018-1019)

Uncertainty component	*Uncertainty (%)*	
	Type A	Type B
Step 1: Reference standard		
Calibration from BIPM/PSDL		0.50*
Long term stability of the secondary standard		0.29
Spectral difference PSDL/IAEA		0.17
Current measurement - Ref. Std.	0.05	0.10
Temperature and pressure correction - Ref. Std.		0.05
Current measurement – Monitor	0.05	0.10
Temperature and pressure correction - Monitor		0.05
Relative combined standard uncertainty in Step 1	*0.07*	*0.62*
Step 2: Instrument to be calibrated		
Current measurement - User Chamber	0.06	0.20
Temperature and pressure correction - User Chamber		0.05
Current measurement – Monitor	0.05	0.10
Temperature and pressure correction - Monitor		0.05
Stability of the monitor chamber		0.09
Difference in radial non-uniformity of the beam		0.17
Chamber positioning		0.01
Relative combined standard uncertainty in Step 2	*0.08*	*0.30*
Relative combined standard uncertainty (Steps 1 + 2)	*0.11*	*0.69*
Standard combined uncertainty (k = 1)	*0.70*	
Relative expanded uncertainty (*k* = 2)	**1.4**	

*In case of the Mo+Mo and W+Mo radiation qualities the relative expanded uncertainty is 1.3% due to the different traceability of reference standard (*IAEA CMCs Identifier in the BIPM KCDB): EUR-RAD-IAEA 1019*.

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