# Chapter II
# X and gamma ray secondary standard metrology

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## *II.1 Introduction*

The Secondary Standards Dosimetry Laboratory (SSDL) role [15, 16, 25, 28–30] is crucial in providing traceability, disseminating calibrations at specific radiation qualities, and appropriately using radiation measuring instruments. An SSDL may be either national or regional. A national SSDL is a laboratory that has been designated by competent national authorities to undertake the duties of necessary radiation dosimetry traceability to national/international standards for country users. A regional SSDL is designated by an intergovernmental agreement or by an international organization not only to carry out national functions but also to provide calibration services and advice to other countries within the concerned geographical area [44].

An SSDL is equipped with secondary standards that are traceable to the primary standard dosimetry laboratories participating in the international measurement system, Primary Standard Dosimetry Laboratories (PSDL) and the Bureau International des Poids et Mesures (BIPM). Figure II.1 illustrates the global metrological links of the international measurement system (SI – Système International) for radiation dosimetry [26].

In 1976, the International Atomic Energy Agency (IAEA) and the World Health Organization (WHO) established an SSDL network called the "IAEA/WHO Network of Secondary Standard Dosimetry Laboratories". The objective of this SSDL network was to improve accuracy in applied radiation dosimetry throughout the world; it is an association of SSDLs that agrees to cooperate to promote the objectives of that network under international auspices [42].

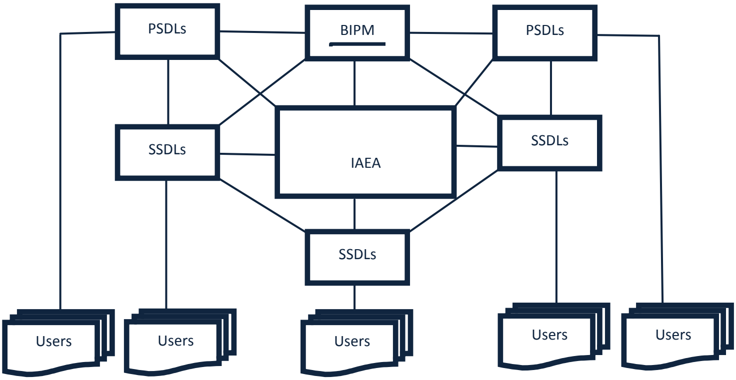

Figure II.1. Global metrological links of the international measurement system [26].

Historically, although the first SSDLs provided mainly radiation therapy-level calibrations, the scope of their work has expanded over the years [45]. Today, many SSDLs provide traceability for amplified range measurements, applied in radiation protection and diagnostic radiology in addition to radiotherapy following the IAEA recommendations and code of practices [15, 16, 27, 30].

The requirements for traceable and reliable calibrations performed at SSDLs are becoming increasingly important, and the demonstration of their competence can be achieved through comparisons and the establishment of a quality system following the International Organization for Standardization (ISO) standard [40]. One important requirement of the quality system is the assessment of the measurement uncertainty and a general guidance on the uncertainty estimation published by ISO [33–36], based on which the IAEA prepared a practical guide for SSDLs on how to assess and report measurement uncertainties [49].

## *II.2 SSDL Responsibilities*

The SSDL responsibilities include but are not limited to the following activities [50]:

- Maintaining secondary standard instruments in agreement with the international measurement system and performing re-calibrations at least every 3 years.
- Performing calibrations of radiation measurement equipment and issuing calibration certificates with all of the necessary information, including the estimated uncertainties.
- Organizing dose comparisons for institutions within the country or region and participating in measurement comparisons within the IAEA/WHO SSDL network and with other standardizing laboratories.
- Cooperating with the IAEA/WHO network and with other metrological laboratories in the exchange of information and improvement of measurement instruments and techniques.
- Documenting and preserving records of all of the calibration procedures and results.
- Keeping up to date on progress in radiation measurement to improve calibration techniques as required, thereby providing a better service to the users of radiation.
- Providing training in radiation measurement, calibration techniques and relevant instrumentation use and maintenance as appropriate to the users of radiation as served by the SSDL.

- Secretariat reporting, at least annually, on the secondary standards status, radiation sources, calibrations performed and related activities.

### *II.3 Determination of a calibration coefficient: The model equation*

Three methods can be used to calibrate instruments in a radiation field: tip-to-tip, substitution or calibration method in a known radiation field [51].

Using the tip-to-tip method, the reference dosimeter and the dosimeter to be calibrated are placed in the radiation beam and irradiated simultaneously.

In calibration by substitution, first, the reference dosimeter is placed at the calibration point to determine the reference output rate of the beam through a set of readings. It is then replaced by the dosimeter to be calibrated, and a similar set of readings is taken.

To perform a calibration in a known radiation field, it is assumed that the basic radiation quantity characterizing the field is already known and that no reference instrument is needed at the time of the irradiation of the dosimeter to be calibrated.

Each method has advantages and disadvantages, and an SSDL may select one or another procedure. Most SSDLs use the substitution method [41]. The calibration coefficient can be easily derived from the substitution method and can be determined in two steps [49]:

Step 1: The radiation beam output rate[1], $\dot{K}_{a,Q}$, of quality Q is determined with the SSDL reference standard, traceable at a PSDL:

$$\dot{K}_{a,Q} = N_{K,Q_0}^{ref} \, M_{corr}^{ref} k_{Q,Q_0} \qquad \text{II.1}$$

where $N_{K,Q_0}^{ref}$ is the SSDL reference standard calibration coefficient for the beam quality $Q_0$; $M_{corr}^{ref}$ is the reference dosimeter reading corrected for the quantities influence; and $k_{Q,Q_0}$ is the factor to account for the difference in beam qualities of the PSDL and the SSDL [27].

Step 2: The instrument to be calibrated is placed at the same position as the SSDL reference standard in the beam of quality Q. The calibration coefficient $N_Q^{user}$ for the beam quality Q of the instrument to be calibrated is determined as the ratio of the output rate $\dot{K}_{a,Q}$, determined in step 1, to the mean reading that is obtained from the instrument to be calibrated and corrected for the influence quantities.

$$N_Q^{user} = \frac{\dot{K}_{a,Q}}{M_{corr}^{user}} k_{source} \qquad \text{II.2}$$

where $k_{source}$ is the correction for the effect of a change in the source position, and $M_{corr}^{user}$ is the reading that is obtained with the user instrument, already corrected for influence quantities.

### *II.4 Dosimetry Protocols: Codes of Practice*

One of the principal goals of the SSDL network in the radiation dosimetry field is to guarantee that the dose that is delivered to patients and/or received by individuals undergoing radiation fields within internationally accepted levels of accuracy. This regulation is accomplished by ensuring that the calibrations of

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[1] The model equation is also valid for integral kerma

instruments that are provided by the SSDLs are correct, emphasizing the participation of the SSDLs in quality assurance programs, promoting the contribution to support dosimetry quality audits and assisting if needed in performing the calibration of equipment in hospitals.

### *II.4.a Radiotherapy*

The Code of Practice TRS 398 [27] determines the absorbed dose for the water methodology in low-, medium- and high-energy photon beams, electron beams, proton beams and heavy-ion beams used for external radiotherapy.

The determination of absorbed dose to water formalism in high-energy photon and electron beams uses an ionization chamber or a dosimeter calibrated in terms of absorbed dose to water in a $Co^{60}$ source.

It is assumed that the absorbed dose to water, $D_w$, is known at a depth of 5 $g/cm^2$ in a water phantom for $Co^{60}$ gamma rays. This determination is realized at the SSDL by means of a calibrated cavity ionization chamber performing measurements in a water phantom. The user chamber is placed with its reference point at the same depth, and its calibration factor $N_{D,w}$ is obtained from

$$N_{D,w} = \frac{D_w}{M} \qquad \text{II.3}$$

where M is the dosimeter reading corrected for influence quantities; recommended reference conditions for the ionization chamber calibration in $Co^{60}$ are given in table II.1.

Medium- or low-energy X rays measuring the chamber must be calibrated in similar-quality beams, but only a few PSDLs have primary standards of absorbed dose to water for kilovoltage X ray qualities [38, 39]. However, it is possible to derive calibration factors in terms of absorbed dose to water from air kerma calibration factors using one of the accepted protocols or Codes of Practice for the dosimetry of X ray beams.

Table II.1: Reference conditions for ionization chamber calibration in $^{60}$Co gamma radiation for absorbed dose in low- and medium-energy X ray beams in standard laboratories.

| | Reference value or reference characteristics | | |
|---|---|---|---|
| | Gamma | X Rays | |
| Influence quantity | $^{60}$ Co | Low | Medium |
| Phantom material | Water | PMMA[c] | Water |
| Phantom size (cm$^3$) | 30×30×30 | 12×12×6 | 30×30×30 |
| Source-chamber distance (SCD) | 100 cm | Specified by user | Specified by user |
| Air temperature | | 20ºC | |
| Air pressure | | 101.3 kPa | |
| Relative humidity | | 50% | |
| Reference point of the ionization chamber | cylindrical[A]<br>plane-parallel[B] | plane-parallel[B] | cylindrical[A] |
| Depth in phantom[D] | 5 g/cm$^2$ | Surface | 2 g/cm$^2$ |
| Field size at the position[D] | | 3×3 cm$^2$ | 10×10 cm$^2$ |

[A] on the central axis at the center of the cavity volume
[B] on the central axis at the outside of the entrance window
[C] water equivalent plastic
[D] of the reference point of the chamber

Typical reference conditions for the ionization chambers calibration in kilovoltage X ray beams are given in table II.1. The reference radiation qualities are those that are recommended by BIPM and their main characteristics are presented in tables II.2 and II.3 [54].

The radiation conditions or dosimetry quantities that were used for X and Gamma ray applied for Protection, Therapy and

Diagnosis are shown in tables II.2 to II.16. In the past, various radiation conditions have been used for the specification of the dose in IR, and there has been ambiguity because the same name has been used for different radiation conditions, expressed by the tube voltage, added filtration, half value layer (HVL) and homogeneity coefficient.

Table II.2: Low-energy X ray qualities recommended by BIPM [54].

| Tube Voltage(kV) | Added Filtration(mm Al) | Half Value Layer(mm Al) | Air Kerma rate(mGy/s) |
|---|---|---|---|
| 10 | -- | 0.037 | 1.00 |
| 25 | 0.208 | 0.169 | 1.00 |
| 30 | 0.372 | 0.242 | 1.00 |
| 50(a) | 3.989 | 2.262 | 1.00 |
| 50(b) | 1.008 | 1.017 | 1.00 |

Table II.3: Medium-energy X ray qualities recommended by BIPM [54].

| Tube Voltage | Added Filtration (mm) | | HVL[1] (mm) | | Air Kerma rate |
|---|---|---|---|---|---|
| kV | Al | Cu | Al | Cu | mGy/s |
| 100 | 3.431 | -- | 4.030 | 0.149 | 0.50 |
| 135 | 2.228 | 0.232 | -- | 0.489 | 0.50 |
| 180 | 2.228 | 0.485 | -- | 0.977 | 0.50 |
| 250 | 2.228 | 1.570 | -- | 2.484 | 0.50 |

[1] Half Value Layer

### *II.4.b Diagnostic Radiology*

Various examination techniques are used in X ray diagnostic radiology and include fluoroscopy, interventional radiological procedures, mammography, Computed Tomography (CT), dental and general radiography. X ray beams with tube voltages from 20 to 150 kV are used.

Table II.4: Radiation qualities for calibrations of diagnostic radiology dosimeters

| Radiation Quality | Radiation beam | Material of an additional filter | Application |
|---|---|---|---|
| RQR | X ray assembly | No phantom | General radiography and dental applications[A] |
| RQA | added filter | Aluminum | Measurements behind the patient[B] |
| RQT | added filter | Cooper | CT applications |
| RQR-M | X ray assembly | No phantom | Mammography applications |
| RQA-M | added filter | Aluminum | Mammography studies |
| W or Rh Anode | added filter | Mo, Rh, Pd and Al | Mammography studies |

[A] free in air

[B] on the image intensifier

The tube voltages in fluoroscopy, CT, dental and general radiography range from 50 to 150 kV; the anode material is usually tungsten. Mammography examinations are conducted with tube voltages between 22 and 40 kV, and various combinations of anode and filtration materials are used; the most common materials are molybdenum anode and molybdenum filtration, but for calibration, we could use also tungsten, molybdenum and Rhodium anode, combined with Aluminum, Molybdenum, Palladium, Rhodium and Silver filtration [41,42,56–58]; see table II.4.

In diagnostic radiology, the specification of radiation qualities is important because the response of all dosimeters depends, at least to a certain extent, on the spectral distribution of the X rays employed. Radiation qualities are usually specified in terms of the X ray tube voltage first HVL and homogeny coefficient [60].

The dosimetry formalism based on air kerma determination is given in detail by the TRS 457 [28], and the recommended radiation qualities are described by the IEC 61267 [29], as presented in Tables II.5 to 8. This Code of Practice generally follows ICRU 74 [34] on patient dosimetry for X rays that are used in medical imaging.

Table II.5: Characterization of non-attenuate radiation quality series RQR; the number 5 is the reference radiation quality [16 and 17].

| Radiation Quality | X ray tube voltage(kV) | First HVL (mm Al) | Homogeneity coefficient |
|---|---|---|---|
| RQR2 | 40 | 1.42 | 0.81 |
| RQR3 | 50 | 1.78 | 0.76 |
| RQR4 | 60 | 2.19 | 0.74 |
| **RQR5*** | **70** | **2.58** | **0.71** |
| RQR6 | 80 | 3.01 | 0.69 |
| RQR7 | 90 | 3.48 | 0.68 |
| RQR8 | 100 | 3.97 | 0.68 |
| RQR9 | 120 | 5.00 | 0.68 |
| RQR10 | 150 | 6.57 | 0.72 |

Table II.6: Characterization of attenuate radiation quality series RQA; number 5 is the reference radiation quality [16 and 17].

| Radiation Quality | X ray tube voltage(kV) | Added Filtration(mm Al) | Nominal first HVL(mm Al) |
|---|---|---|---|
| RQA2 | 40 | 4 | 2.2 |
| RQA3 | 50 | 10 | 3.8 |
| RQA4 | 60 | 16 | 5.4 |
| **RQA5*** | **70** | **21** | **6.8** |
| RQA6 | 80 | 26 | 8.2 |
| RQA7 | 90 | 30 | 9.2 |
| RQA8 | 100 | 34 | 10.1 |
| RQA9 | 120 | 40 | 11.6 |
| RQA10 | 150 | 45 | 13.3 |

Table II.7: Characterization of mammography radiation quality series RQR-M and RQA-M; number M2 is the reference radiation quality [16,17 and61].

| Radiation Quality | X ray tube voltage  kV | Added Filtration mm | Nominal first HVL mm Al |
|---|---|---|---|
| RQR-M1 | 25 | 0,03 Mo | 0.28 |
| **RQR-M2*** | **28** |  | **0.31** |
| RQR-M3 | 30 |  | 0.33 |
| RQR-M4 | 35 |  | 0.36 |
| RQA-M1 | 25 | 0,03 Mo+2 Al | 0.56 |
| RQA-M2 | 28 |  | 0.60 |
| RQA-M3 | 30 |  | 0.62 |
| RQA-M4 | 35 |  | 0.68 |

Table II.8: Characterization of Computed Tomography radiation quality series RQT; number 9 is the reference radiation quality [16 and 17].

| Radiation Quality | X ray tube voltage(kV) | Added Filtration(mm Cu) | Nominal first HVL(mm Al) |
|---|---|---|---|
| RQT8 | 100 | 0.2 | 6.9 |
| **RQT9*** | **120** | **0.25** | **8.4** |
| RQT10 | 150 | 0.3 | 10.1 |

### *II.4.c Radiation Protection*

Occupational radiation protection is a major component of the support for radiation safety provided by the IAEA Member States. The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) presents the requirements for occupational radioprotection [43 and 44].

Occupational exposure to ionizing radiation can occur in industry, medical institutions, research establishments, universities and nuclear fuel cycle facilities. The IAEA Technical Safety Report 16 [43] provides guidance on the establishment and operation of calibration facilities for radiation monitoring instruments based on the operational quantities. The recommended radiation qualities were established by the International Organization for Standardization [18–21] and are provided in Tables II.9 to 13.

Table II.9: Radionuclide sources that are used for the production of gamma radiation.

| Radionuclide | Energy (MeV) | Half-life (days) | Air kerma rate[A] (µGy.h$^{-1}$.m$^{2}$.MBq$^{-1}$) |
|---|---|---|---|
| $^{60}$Co | 1.1733<br>1.3325 | 1924 | 0.31 |
| $^{137}$Cs | 0.6616 | 10976 | 0.079 |
| $^{241}$Am | 0.05954 | 84753 | 0.003 |

[A] The air-kerma rate constant is valid only in the case of an unshielded point source. It is therefore given only as a guide and not as a means of determining the air-kerma rates.

Table II.10: Characteristics of low air kerma rate series

| Tube Potential (kV) | Mean energy (keV) | Additional Filtration (mm) | | | | First HVL (mm) |
|---|---|---|---|---|---|---|
| | | Pb | Sn | Cu | Al | |
| 10 | 8.5 | | | | 0.3 | 0.058 Al |
| 20 | 17 | | | | 2.0 | 0.42 Al |
| 30 | 26 | | | 0.18 | 4.0 | 1.46 Al |
| 35 | 30 | | | 0.25 | | 2.20 Al |
| 55 | 48 | | | 1.2 | | 0.25 Cu |
| 70 | 60 | | | 2.5 | | 0.49 Cu |
| 100 | 87 | | 2.0 | 0.5 | | 1.24 Cu |
| 125 | 109 | | 4.0 | 1.0 | | 2.04 Cu |
| 170 | 149 | 1.5 | 3.0 | 1.0 | | 3.47 Cu |
| 210 | 185 | 3.5 | 2.0 | 0.5 | | 4.54 Cu |
| 240 | 211 | 5.5 | 2.0 | 0.5 | | 5.26 Cu |

Table II.11: Characteristics of the narrow spectrum series.

| Tube Potential (kV) | Mean energy (keV) | Additional Filtration (mm) | | | | First HVL (mm) | Second HVL (mm) |
|---|---|---|---|---|---|---|---|
| | | Pb | Sn | Cu | Al | | |
| 10 | 8 | | | | 0.1 | 0.047Al | 0.052 Al |
| 15 | 12 | | | | 0.5 | 0.14 Al | 0.16 Al |
| 20 | 16 | | | | 1.0 | 0.32 Al | 0.37 Al |
| 25 | 20 | | | | 2.0 | 0.66 Al | 0.73 Al |
| 30 | 24 | | | | 4.0 | 1.15 Al | 1.30 Al |
| 40 | 33 | | | 0.21 | | 0.84 Cu | 0.091Cu |
| 60 | 48 | | | 0.6 | | 0.24 Cu | 0.26 Cu |
| 80 | 65 | | | 2.0 | | 0.58 Cu | 0.62 Cu |
| 100 | 83 | | | 5.0 | | 1.11 Cu | 1,17 Cu |
| 120 | 100 | | 1.0 | 5.0 | | 1.71 Cu | 1.77 Cu |
| 150 | 118 | | 2.5 | | | 2.36 Cu | 2.47 Cu |
| 200 | 164 | 1.0 | 3.0 | 2.0 | | 3.99 Cu | 4.05 Cu |
| 250 | 208 | 3.0 | 2.0 | | | 5.19 Cu | 5.23 Cu |
| 300 | 250 | 5.0 | 3.0 | | | 6.12 Cu | 6.15 Cu |

Table II.12: Characteristics of the wide spectrum series.

| Tube Potential (kV) | Mean energy (keV) | Additional Filtration (mm) | | First HVL | Second HVL |
|---|---|---|---|---|---|
| | | Tin | Copper | mm Cu | mm Cu |
| 60 | 45 | | 0.3 | 0.18 | 0.21 |
| 80 | 57 | | 0.5 | 0.35 | 0.44 |
| 110 | 79 | | 2.0 | 0.96 | 1.11 |
| 150 | 104 | 1.0 | | 1.86 | 2.10 |
| 200 | 137 | 2.0 | | 3.08 | 3.31 |
| 250 | 173 | 4.0 | | 4.22 | 4.40 |
| 300 | 208 | 6.5 | | 5.20 | 5.34 |

Table II.13: Characteristics of the high air kerma rate series

| Tube Potential (kV) | Mean Energy (keV) | Additional filtration (mm) | | | HVL (mm) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | First | | Second | |
| | | Al | Cu | Air | Al | Cu | Al | Cu |
| 10 | 7.5 | | | 750 | 0.036 | 0.010 | 0.041 | 0.011 |
| 20 | 12.9 | 0.15 | | 750 | 0.12 | 0.007 | 0.16 | 0.009 |
| 30 | 19.7 | 0.52 | | 750 | 0.38 | 0.013 | 0.60 | 0.018 |
| 60 | 37.3 | 3.2 | | 750 | 2.42 | 0.079 | 3.25 | 0.11 |
| 100 | 57.4 | 3.9 | 0.15 | 750 | 6.56 | 0.30 | 8.05 | 0.47 |
| 200 | 102 | | 1.15 | 2250 | 14.7 | 1.70 | 15.5 | 2.40 |
| 250 | 122 | | 1.6 | 2250 | 16.6 | 2.47 | 17.3 | 3.29 |
| 280 | 146 | | 3.0 | 2250 | 18.6 | 3.37 | 19.0 | 3.99 |
| 300 | 147 | | 2.5 | 2250 | 18.7 | 3.40 | 19.2 | 4.15 |