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Reference Dosimetry of High-Energy Therapy Electron Beams with Ionisation Chambers

Recommendations No. 10, Revision 2019

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Contents

1. Introduction

The scope of the recommendations "**Reference Dosimetry of High-Energy Therapy Electron Beams with Ionisation Chambers"** is to provide the user with guidelines for how to perform reference dosimetry of high-energy electron beams with an ionisation chamber calibrated at the Swiss Federal Institute of Metrology (METAS). Additionally, cross calibration of a field dosimeter is described.

The structure of these recommendations is as follows: In the chapter "Legal aspects" the main legal aspects concerning dosimetry are mentioned. In "Recommended ionisation chambers and phantoms" recommendations for the instrumentation are given. The chapter "Determination of absorbed dose to water" describes how to determine the dose and how to get the necessary correction factors for that purpose. The uncertainties of absorbed dose measurements are discussed in chapter 5. In the appendices the calculation of correction factors, the calibration of a field dosimeter and the calibration procedure at METAS are covered.

The present recommendations are a revised version of the Swiss Society of Radiobiology and Medical Physics (SSRMP) recommendations No. 10, 2002. As for the former recommendations, these recommendations are based on the international guideline of the IAEA code of practice [1]. However, radiation quality correction factors differ between the Swiss protocol and the IAEA code of practice (see Appendix 7).

The present document covers high-energy electron beams generated by an accelerator with nominal energies in the range of 4 MeV to 23 MeV.

For the dosimetry of high-energy photon beams the user should refer to SSRMP Recommendations No 8, 2018 [2].

The present recommendations provide a methodology only for the determination of absorbed dose to water *at the reference point* according to the conditions stated in the verification certificate. Except for the determination of the central-axis depth-dose curve (see Appendix 6), the dosimetry at any other point is outside the scope of this document.

It lies within the responsibility of a certified medical physicist to apply these recommendations in a suitable manner. It is recommended to apply the four-eyes principle during reference dosimetry to avoid miscalibration. Additionally, external checkings as provided for example by an independent dosimetry audit should be performed according to SSRMP recommendations no. 11 [3].

2. Legal aspects

Effective are the Radiological Protection Act of March 22, 1991 [4], the Radiological Protection Ordinance of April 26, 2017 [5], the Ordinance of Units of November 23, 1994 [6], and the Ordinance of Accelerators of April 26, 2017 [7]. The verification refers more specifically to the general provisions of the Ordinance of Measuring Instruments of February 15, 2006 [8] and to the Ordinance of the Federal Department of Justice and Police (EJPD) for Measurement Devices for Ionizing Radiation (OMDIR) of December 7, 2012 [9].

a Quantities and units

In radiation therapy, absorbed dose to water is the quantity of interest. According to Article 13 of the Ordinance of Units, absorbed dose is measured in gray (Gy).

b Verification and use of dosimeters

Two types of dosimeters are distinguished:

- Reference dosimeter instruments, consisting of an ionisation chamber, an electrometer, a radioactive check source and appropriate chamber sheaths, are verified at METAS. A **verification** at METAS includes the determination of dosimeter-specific calibration coefficients as well as the stability and functionality testing of the dosimeter system. METAS provides a calibration coefficient to convert measured charge into dose to water.

- Field dosimeter instruments may be used for routine dosimetry. By using them it can be avoided that the reference dosimeter is damaged due to frequent use. A damaged reference dosimeter means that the user has no possibility to adjust the delivered dose of their MeV beams. The recommended procedure for the calibration of a field dosimeter consists of a comparison with a reference dosimeter as described in Appendix 1.

  Parts of a reference dosimeter system may also be part of a field dosimeter system.

The verification of reference dosimeters is described in OMDIR [9]. The most important points are the following:

- **Verification:** The reference dosimeter must be verified every 4 years. The competent organisation for the verification is METAS. The dosimeter system has to be calibrated at the radiation qualities at which it will be used. During verification at METAS, the check source response is also measured. It must be assured that the dosimeter system can be calibrated with an accuracy of ± 3 % and at a confidence level of 95 %.

- **Handling:** If the dosimeter is used more than once per half year, the user has to check it for constant response at least half-yearly intervals, by means of the radioactive check source, a thermometer and a barometer with calibrations traceable to national standards [9]. If the dosimeter is used less frequently, the constancy has to be checked before each usage. These checks have to be documented. The deviation of the result of the check relative to the value given in the verification certificate must be within ± 1.0 % (Appendix 2).

The certified medical physicist is responsible for the checks of the reference dosimeter instruments and the cross-calibration of the field dosimeters [7].

3. Recommended ionisation chambers and phantoms

Chambers used for reference dosimetry in radiation therapy need to have a METAS approbation [9, 10]. It is generally accepted [11, 12] that well-guarded plane-parallel ionisation chambers, such as the Scanditronix NACP-02 or the PTW 34001 Roos, have a negligible perturbation correction factor. In a "well-guarded" plane-parallel ionisation chamber, the collecting electrode is surrounded by a guard electrode with a width of not smaller than 1.5 times the cavity height [12]. These chambers are recommended as chambers of a reference dosimeter system for all electron beam qualities. The reference point for plane-parallel chambers is taken to be at the centre of the inner surface of the entrance window. During measurements, this point must be considered to be the effective point of measurement of the chamber and be positioned at the reference depth in the phantom.

These ionisation chambers should be open to the ambient air and in equilibrium with the ambient air pressure. Water is recommended as the reference medium for measurements in electron beams. The water phantom should be a full-scatter phantom and should extend at least 5 $g \cdot cm^{-2}$ outside all beam edges and at least 5 $g \cdot cm^{-2}$ beyond the maximum depth of measurement.

In a horizontal electron beam, the window of the phantom should be of PMMA or polystyrene and of thickness d_{win} between 0.2 cm and 0.5 cm. The water equivalent thickness of the phantom window (in $g \cdot cm^{-2}$) should be taken into account when positioning the chamber at the desired measurement depth. The thickness is calculated as the product $d_{win} \cdot \rho_{pl}$, where ρ_{pl} is the density of the plastic (in $g \cdot cm^{-3}$). For the commonly used plastics PMMA and clear polystyrene, the nominal values $\rho_{PMMA} = 1.19\ g \cdot cm^{-3}$ and $\rho_{polyst} = 1.06\ g \cdot cm^{-3}$ should be used.

For beam qualities $R_{50} < 4\ g \cdot cm^{-2}$ ($E_0 \leq 10$ MeV) PMMA phantoms could be used, but using them for reference dosimetry is not recommended.

For ionisation chambers that are not waterproof, a close-fitting waterproof plastic cap (made of low-Z materials, e.g. PMMA) must be used. The wall of the cap should be sufficiently thin (≤ 1.0 mm) to allow the chamber to achieve thermal equilibrium with the phantom in typically 2 to 3 minutes per degree of temperature difference. The cap should be vented to allow the air pressure in the chamber to reach ambient air pressure quickly. The cap must then be considered a component of the dosimeter and the calibration coefficients are only valid for measurements made using the same cap as the one that was used for the verification at METAS.

4. Determination of the absorbed dose to water

In order to obtain reliable measurement results, a stability check of the dosimeter is recommended before and after every measurement, using the radioactive check source, the thermometer and barometer according to Appendix 2.

a Absorbed dose to water at the reference depth

The absorbed dose to water at the reference depth in water for a certain radiation quality Q (in absence of the chamber) is given by:

$$\boldsymbol{D_{W,Q} = N_{W,Q} \cdot M_Q} \qquad (1)$$

with $N_{W,Q} = N_{W,Co60} \cdot k_Q$ and $M_Q = M \cdot k_{Tp} \cdot k_S \cdot k_f \cdot k_{pol}$

$D_{W,Q}$	:	Absorbed dose to water in Gy at the reference depth in water for the radiation beam quality Q in the absence of the chamber.
Q	:	Radiation beam quality
$N_{W,Q}$	:	Absorbed dose to water calibration coefficient in Gy/C under reference conditions for the radiation beam quality Q
M_Q	:	Corrected dosimeter reading (in C)
$N_{W,Co60}$	:	Absorbed dose to water calibration coefficient in Gy/C under reference conditions for the reference radiation beam quality of ^{60}Co (provided by METAS)
k_Q	:	Radiation beam quality correction factor
M	:	Non-corrected dosimeter reading (in C)
k_{Tp}	:	Air density correction factor
k_S	:	Ion recombination correction factor
k_f	:	Correction factor for humidity
k_{pol}	:	Correction factor for polarity

b Reference conditions

The reference conditions are those conditions for which the calibration coefficient $N_{W,Co60}$ for absorbed dose to water $D_{W,Co60}$ of a dosimeter is specified. The calibration coefficient can be used under different conditions but has to be corrected (see following sections).

The reference conditions to which the verification by METAS refers to are:

Temperature T_0	293.15 K (20 °C)
Absolute air pressure p_0	1013.25 hPa
Relative humidity r_F	50%
Charge collection efficiency	100%
Voltage and polarity	according to the verification certificate
Chamber reference point	at the centre of the inner surface of the chamber entrance window
Radiation quality	^{60}Co
Source to chamber distance (ref. point)	100 cm
Field size	10 cm x 10 cm (50% Isodose) at the chamber's reference point

The following conditions for measurements are those under which the verification by METAS is valid:

Depth in water	at z_{ref} of the corresponding beam quality

Source to surface distance (SSD)	100 cm
Field size	15 cm x 15 cm at the surface of the phantom
Radiation beam quality index	R_{50} between 1.70 g·cm^{-2} and 8.80 g·cm^{-2}

The reference depth z_{ref} is given by [1,13]

$$z_{ref} = 0.6 \cdot R_{50} - 0.1 \text{ g·cm}^{-2} \quad (R_{50} \text{ in g·cm}^{-2}) \tag{2}$$

where R_{50} is the depth in water at which the absorbed dose is 50% of its value at dose maximum, measured on the beam central axis at an SSD of 100 cm (field size 15 cm x 15 cm). z_{ref} is close to the depth of the absorbed-dose maximum z_{max} at beam qualities for which $R_{50} < 4$ g·cm^{-2} ($E_0 < 10$ MeV). At higher beam qualities z_{ref} is larger than z_{max}. The determination of R_{50} is described in Appendix 5.

It is recommended to use a field size similar to the field size used for calibration, in order to have the same energy spectrum. As electron fields are usually delimited by the fixed aperture of an electron applicator, the exact field size depends on mechanical properties of the system and may therefore differ from the field size used during verification. It is the responsibility of the user to use a field size as close as possible to the field size mentioned in the verification certificate (15 cm x 15 cm at the surface of the phantom at an SSD of 100 cm).

c Air density correction k_{Tp}

For accurate measurements it is necessary to correct for any difference between the air density in the chamber at the time of measurement and the density for which the calibration coefficient applies. The factor k_{Tp} corrects for the influence of air temperature and air pressure on the air density in the open cavity volume:

$$k_{Tp} = \frac{p_0 \cdot T}{p \cdot T_0} \tag{3}$$

T is the temperature of the air in the chamber and p is the measured ambient air pressure. The reference values p_0 and T_0 are given in chapter 4b.

d Ion recombination correction k_S

The incomplete efficiency in collecting charge in the cavity volume due to ion recombination requires the use of a correction factor k_S. The correction depends on the geometry of the ionisation chamber, the voltage applied to the chamber, and the dose per accelerator pulse. In the case of a pulsed radiation, the correction factor for recombination becomes rather important. For measurements in pulsed electron beams a correction for ion recombination shall be made. Appendix 4 provides a description on how to measure or calculate the ion recombination correction factor for pulsed beams.

e Humidity correction k_f

It is difficult to determine the relative humidity of the air in a chamber, particularly when it is immersed in a water phantom. However, the correction for any difference between the humidity at the time of measurement and 50 % relative humidity, for which the calibration coefficient applies, is small (< 0.1 %) for a relative humidity between 20 % and 70 % and a temperature between 15 °C and 25 °C. Therefore,

$$k_f = 1 \tag{4}$$

f Polarity effect correction k_{pol}

It is mandatory to use the ionisation chamber with the same electrometer and with the same polarising voltage as during the calibration at METAS. Therefore, a polarity effect correction is not needed as it is already considered in the calibration coefficient.

$$k_{pol} = 1 \tag{5}$$

g Correction k_Q for radiation beam quality Q

The radiation beam quality correction factor k_Q can be derived using a polynomial function $f(R_{50})$ of third degree, which was determined experimentally at METAS (Appendix 7).

$$\boldsymbol{k_Q} = \boldsymbol{f}(R_{50}) = \boldsymbol{a} \cdot {R_{50}}^3 + \boldsymbol{b} \cdot {R_{50}}^2 + \boldsymbol{c} \cdot R_{50} + \boldsymbol{d} \tag{6}$$

The values *a, b, c* and *d* are stated in the verification certificate of the dosimeter. See Appendix 5 on how to determine R_{50}. The function $f(R_{50})$ is only valid for the type of ionisation chamber mentioned in the verification certificate and for values of R_{50} between 1.70 g·cm^{-2} and 8.80 g·cm^{-2} (see Appendix 7). For beams with R_{50} outside this range, values of k_Q must be taken from table 7.III (page 82) provided in TRS 398 [1].

5. Typical uncertainties in absorbed dose determinations

The evaluation of uncertainties in these recommendations follows the guidance given by the IAEA [1]. When a reference dosimeter is used for the determination of absorbed dose to water in the user's beam, the uncertainties in the different physical quantities or procedures that contribute to the dose determination can be divided into two steps. Step 1 considers uncertainties due to the calibration of a reference dosimeter in terms of $N_{W,Q}$ at the verification laboratory (in contrast to the IAEA document, the uncertainty of k_Q is included here). Step 2 deals with the absorbed dose determination in the user's beam and includes the uncertainties associated with the measurements at the reference point in a water phantom. Combining the squared uncertainties in the various steps yields the combined standard uncertainty for the determination of the absorbed dose to water at the reference point.

The uncertainties for Step 1 are the ones estimated by METAS and which are stated on the verification certificate. The uncertainties for Step 2 are taken from [14]. They are only valid for nominal energies in the range of 6 - 21 MeV (outside this range the uncertainties have to be estimated by the user).

The indicated values are expanded uncertainties (two times the standard uncertainties). A measured value and the corresponding expanded uncertainty represent the interval that contains the value of the measured quantity with a probability of 95 % (with coverage factor *k=2*).

Typical uncertainties are as follows:		expanded uncertainty (*k=2*)
Step 1:	Verification Laboratory	
	Calibration coefficient $N_{W,Q}$	2.7%
Step 2:	User's Beam	
	Corrected dosimeter reading M_Q	1.4 %
	Establishment of reference conditions	0.9 - 1.4% (6 - 21 MeV)
Combined standard uncertainty in $D_{w,Q}$		**3.2 – 3.4%**

Appendix 1: Cross-Calibration of a field dosimeter

The recommended procedure for the cross-calibration of a field dosimeter by comparison with a reference dosimeter is as follows:

1) Carry out the comparison using the same radiation qualities that the field dosimeter will subsequently be used to measure.

2) Measure the beam quality index of each beam in order to derive the appropriate calibration coefficient for the reference dosimeter.

3) Compare the dosimeter readings (in C) of the reference dosimeter and the field dosimeter by simultaneous irradiation in an appropriate water phantom. The comparison should be performed at reference conditions as described in chapter 4b, but with an appropriate separation of the chamber centres of 3 cm and with each chamber equidistant from the beam axis.

4) In order to minimise any influence of a non-uniformity of the beam on the calibration coefficient the chambers should then be interchanged, the readings repeated and averaged.

If the chambers cannot be measured simultaneously then they can be measured one after the other, centred on the beam axis.

5) Use the same waterproof cap on the reference chamber (if the reference chamber is not waterproof) as when verified at METAS; similarly the waterproof cap used on the field dosimeter in this calibration should be used in all subsequent measurements.

6) Correct the readings of each dosimeter to reference conditions following the procedures described in chapter 4. If the chambers are at identical temperature and pressure the corrections $k_{T,p}$ will cancel out.

The calibration coefficient for the field dosimeter is given by:

$$N_{W,Q}^{F} = \left[\frac{k_{Tp}^{R}\, k_{S}^{R} M^{R}}{k_{Tp}^{F}\, k_{S}^{F} M^{F}}\right] N_{W,Q}^{R} \tag{7}$$

M is the uncorrected dosimeter reading (in C). The superscripts *R* and *F* represent the reference and field dosimeters, respectively.

If the measuring conditions are identical and the dosimeters of identical type, then the formula is reduced to:

$$N_{W,Q}^{F} = \left[\frac{M^{R}}{M^{F}}\right] N_{W,Q}^{R} \tag{8}$$

Appendix 2: Radioactive check source measurements

Radioactive check source measurements are performed to check the functionality of the calibrated measurement instruments (chamber + electrometer). It is recommended to do the check source measurements before and after each calibration of megavoltage beams.

A stability check source usually consists of one or more radioactive sources (often foils) which are situated in a shielded container and which can be brought into a reproducible geometrical relationship with the ionisation chamber. The radionuclide usually used is ^{90}Sr.

A check source type is often designed for a particular type of chamber or can be used with different holders for different chambers. It is often observed that the ionisation current from the chamber varies as the chamber is rotated. In this case a mark is usually engraved on the stem of the chamber by the manufacturer and this mark should be aligned with a corresponding mark on the container of the check source.

If the stability check source has recently been in temperature conditions different from those in the place of measurement, then sufficient time should be allowed for the check source to reach the new temperature before taking readings; this may take several hours. To monitor its temperature, a check source should be provided with a thermometer that can be inserted into a hole in the container. The calibration of the thermometer should be traceable to national standards.

Time should be allowed after inserting a chamber into the chamber holder to allow the chamber to achieve thermal stability and temperature equilibrium with the check source; about 10 min should normally be sufficient.

The verification of the reference dosimeter has to be considered invalid if, after correction for air density and the decay of the source, the measured current differs by more than 1 % from the check source current quoted in the verification certificate of the chamber. If the cause of the discrepancy cannot be identified and rectified (e.g. broken cable), the dosimeter must be checked and verified again by METAS.

The expected ionisation current of the check source measurement at the date of measurement can be calculated as follows:

$$I_e = \frac{I_k}{k_{Tp}} \cdot e^{-\ln(2)\cdot\frac{t}{T_{1/2}}} \tag{9}$$

with:

I_k	ionisation current in pA for the check source as documented in the verification certificate
I_e	expected ionisation current of the check source measurement
$e^{-\ln(2)\cdot\frac{t}{T_{1/2}}}$	decay factor for the time t elapsed between the verification date and the actual date
$T_{1/2}$	half-life of check source according to the verification certificate of METAS
k_{Tp}	correction factor for air density

Appendix 3: Determination of temperature and pressure

To determine the air temperature *T* and the air pressure *p* a thermometer and a barometer with calibrations traceable to national standards have to be used [9].

The temperature *T* of the air in a chamber should be taken as equal to the temperature of the water phantom, if the chamber is in temperature equilibrium with the surrounding water. Note that due to evaporation the water temperature will usually be up to one degree below the room temperature. The point of temperature measurement should be as close to the cavity volume as possible. To reach thermal equilibrium between the ionisation chamber and the water phantom it typically takes 2 to 3 minutes per degree of temperature difference. The phantom should be close to thermal equilibrium with its surroundings in order to avoid temperature drifts. It is recommended to stir the water in the phantom before starting a measurement in order to obtain a homogeneous temperature distribution.

Appendix 4: Determination of the ion recombination correction for pulsed radiation

For pulsed radiation the ion recombination correction may amount to 1% or even more in an electron beam of a typical medical linear accelerator.

For pulsed radiation, the ion recombination correction factor k_S depends on the chamber geometry, the applied polarising voltage, and the dose per macro pulse [15].

There are different options to determine k_S. It is either possible to calculate k_S for example as described in DIN 6800-2 [16]. Alternatively, there is a method to measure k_S based on the fact that ion recombination gives rise to an approximately linear relation between *1/M* and *1/U* under near saturation conditions (k_S < 1.05), where *M* is the non-corrected dosimeter reading (arbitrary units) and *U* the polarising voltage. The method of measuring the ion recombination correction is to take dosimeter readings for equal amounts of radiation (in C) for multiple (>2) different polarising voltages (at least a factor of two between the minimum and maximum voltage) and to plot the function $f: \frac{1}{U} \rightarrow \frac{1}{M}$. The reading under complete saturation, M_S, is then the inverse of the intercept of a linear plot to the data with the *1/M* axis; i.e. $\lim_{U \to \infty} f\left(\frac{1}{U}\right) = \frac{1}{M_S}$. The corresponding ion recombination correction factor to apply is then given by:

$$k_S = \frac{M_S}{M} \tag{10}$$

where *M* is the non-corrected dosimeter reading (in C) corresponding to the normally applied polarisation voltage.

Appendix 5: Beam quality specification

a Choice of beam quality index

For electron beams the beam quality index is defined as the half-value depth in water R_{50}. This is the depth in water (in g·cm^{-2}) at which the absorbed dose is 50% of the absorbed-dose maximum, measured on the beam central axis, with a source to surface distance of 100 cm and a field size at the phantom surface of 15 cm x 15 cm for all beam qualities (i.e. in the same measurement conditions as at METAS; see appendix 7.b). If an applicator for a field size of 15 cm x 15 cm is not available, it is the responsibility of the user to choose a field size where R_{50} differs minimally (< 1 g·cm^{-2}) from that of a 15 cm x 15 cm field.

b Measurement of beam quality

For all beam qualities the preferred choice of detector for the measurement of R_{50} is a well-guarded plane-parallel chamber. A water phantom is used. The beam should be oriented in the vertical direction (perpendicular to the water surface) and the direction of measurement for the central axis depth dose scan should be from a sufficient depth towards the water surface.

Ion recombination corrections are required at all depths. They may be derived from a reduced set of representative measurements on the beam central axis, for example near the surface, at the ionisation maximum and at depths corresponding to 90% and 50% of the ionisation maximum.

Using an ionisation chamber, the measured quantity is the half-value depth in terms of ionisation current $R_{50,ion}$. This is the depth in water (in g·cm^{-2}) on the beam central axis where the ionisation current is 50% of its maximum value. The half-value depth in terms of absorbed dose, R_{50}, is then obtained using [1,16]

$$R_{50} = 1.029 \cdot R_{50,ion} - 0.06 \text{ g·cm}^{-2} \text{ (where } R_{50,ion} \leq 10 \text{ g·cm}^{-2}) \qquad (11)$$

As an alternative to the use of an ionisation chamber, other detectors (diodes, diamonds etc.) may be used to determine R_{50} directly. In this case the user must verify that the detector is suitable for depth-dose measurements by test comparisons with an ionisation chamber for a set of representative beam qualities.

Appendix 6: Determination of the absorbed depth-dose distribution from measurement of the ion depth-dose

Ionisation chamber measurements at depth can be converted to absorbed depth-dose distribution by taking into account the mean energy of the electrons at each point of measurement. This conversion along the central axis can be performed according to the IAEA code of practice [1] (Appendix 7.7.1; p. 85 and B.4; p. 150-151).

Appendix 7: Calibration of a reference dosimeter at METAS

METAS typically renews years its calibration of the absorbed dose to water standard for Cobalt radiation (^{60}Co, half-life 5.27 years) every six to seven years using the water calorimeter primary standard. Additionally, about every 10 years, Fricke dosimetry is also done for high energy electron fields that are generated by METAS's electron accelerator in the energy range from 4 MeV to 21 MeV. From these measurements, several internal secondary standards are calibrated for both ^{60}Co and high-energy electron beams. These secondary standard dosimeters are ionisation chambers of type Scanditronix NACP-02 read out by Keithley 6517 electrometers. The k_Q values for different chamber types are derived by cross-calibrating them with these secondary standards. These measurements need to be performed before a new type of chamber can be calibrated. Figure 1 shows the process for the metrological traceability of the calibration of an ionization chamber to be used in reference dosimetry in a radiotherapy centre.

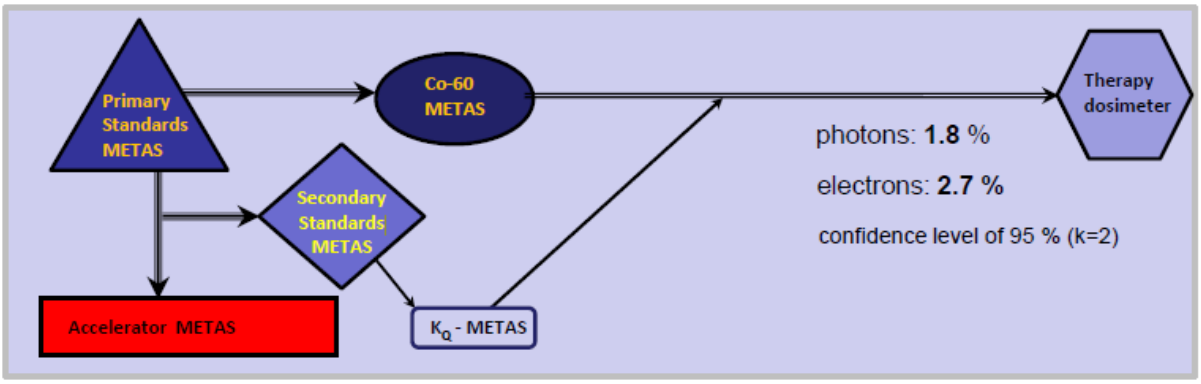

Figure 1: Schematic overview of the metrological traceability in the calibration of the ionisation chamber to be used for reference dosimetry in a radiotherapy centre.

a Experimental determination of the calibration coefficient $N_{W,60Co}$ for standards used in reference dosimetry at radiotherapy centres

For the determination of the calibration coefficient $N_{W,60Co}$ for the absorbed dose to water in the ^{60}Co reference beam, the ionisation chamber is irradiated using of a General Electric Alcyon II type irradiation unit. The dose rate provided by this ^{60}Co source (i.e. the absorbed dose to water per minute under reference conditions) has been previously determined by means of the METAS water calorimeter primary standard.

The calibration coefficient $N_{W,60Co}$ is determined for the following reference conditions: A reference plane is defined perpendicular to the central beam axis of the radiation field at a distance of 1.0 m from the focal point of the ^{60}Co source. The inner surface of the entrance window of the plane-parallel ionisation chamber that is to be calibrated is positioned at this reference plane. The entrance window of the ionisation chamber is oriented such that it points towards the source. The ionisation chamber, either inherently waterproof or embedded in a waterproof sleeve, is positioned in the METAS water phantom (60 x 60 x 60 cm^3) such that the effective water area density along the beam path is 5.0 g/cm^2. The transverse dimension of the beam profile in the reference plane is 10 x 10 cm^2.

b Experimental determination of the radiation quality correction factors k_Q

Radiation beam quality correction factors k_Q are experimentally determined by a direct comparison of the calibration coefficient determined for the respective beam quality index R_{50} and the calibration coefficient determined in the ^{60}Co beam. This procedure is applied for several secondary standard ionisation chambers of the same model, and is then repeated at several beam qualities indexes R_{50} between 1.75 g/cm^2 and 8.54 g/cm^2. The radiation fields are provided by the METAS microtron type accelerator (Model Scanditronix M22) which provides a pulsed primary electron beam at typically 100 Hz and 3.5 µs pulse width.

For the calibration measurements, the ionisation chambers are positioned in the METAS water phantom such that the effective water depth along the beam path is z_{ref} and the distance between the beam focus and the phantom surface (SSD) is 100 cm with a field size of 15 x 15 cm^2 at the surface. The experimental conditions are identical to the conditions applied for the calibration of secondary standards.

c Determination of a semi-empirical model for the calculation of k_Q radiation quality correction factors

In the framework of its calibrations provided to Swiss centres for radiotherapy, METAS has gained extensive data on calibration coefficients for two types of ionisation chambers and various electron beam qualities. Based on this data, a semi-empirical model has been developed that uses the relationship "$k_Q = a \cdot R_{50}^3 + b \cdot R_{50}^2 + c \cdot R_{50} + d$" to predict k_Q as a function of the radiation quality index R_{50}. The parameters *a*, *b, c* and *d* were fitted to the k_Q-values that were experimentally determined in the accelerator radiation field. An analysis of the METAS calibration coefficient database, acquired up until the year 2008, showed that two sets of fit parameters *a*, *b, c* and *d* are able to accurately describe k_Q for all the ionisation chamber types used so far. One set of fit parameters describes the PTW Roos ionisation chamber type 34001 and a second set of parameters is for the Scanditronix chamber type NACP-02.

So far, these are the only two types of ionization chamber that have been used for electron beam reference dosimetry in Swiss radiotherapy centres. If in the future other ionization chamber types (or upgrades of the already approved models) will be used by Swiss centres in electron beam reference dosimetry, the validation of the appropriate model for the prediction of k_Q will need to be done as part of the approbation process for the (new) chamber type [8,9].

Appendix 8: List of symbols

$D_{W,Q}$:	absorbed dose to water at the radiation quality Q
d_{win} :	thickness of entrance window of phantom
E_0 :	nominal mean energy of an electron beam at the phantom surface
F :	as superscript: field dosimeter
I_e :	expected value for the check source ionisation current at the given date (instrument reading, when using the radioactive check source)
I_k :	reference value for the check source ionisation current (instrument reading, when using the radioactive check source)
k_{TP} :	air density correction factor
k_S :	ion recombination correction factor
k_f :	correction factor for humidity
k_{pol} :	correction factor for polarity
k_Q :	correction factor for a radiation quality Q different from the radiation quality of ^{60}Co, at which the dosimeter has been calibrated
M :	non-corrected dosimeter reading
M_Q :	corrected dosimeter reading
M_S :	reading of the dosimeter under complete saturation
$N_{W,Co60}$:	calibration coefficient obtained in the course of the verification to convert the dosimeter reading to absorbed dose to water at the radiation quality of ^{60}Co
$N_{W,Q}$:	calibration coefficient to convert the dosimeter reading to absorbed dose to water at the radiation quality Q
p, p_0 :	absolute air pressure under measurement, resp. reference conditions
Q :	radiation quality (corresponds to R_{50})
R :	as superscript: reference dosimeter
R_{50} :	depth in water in g/cm^2 at which the absorbed dose is 50% of its value at dose maximum, measured along the beam central axis
$R_{50,ion}$:	depth in water in g/cm^2 at which the ionisation current is 50% of its maximum, measured along the beam central axis
r_F :	relative humidity of the air
ρ_{pl} :	density of the phantom window in g/cm^3 of the material pl (plastic)
SSD :	Source to Surface Distance
t:	time elapsed between the reference date of calibration and the date of measurement
$T_{1/2}$:	half-life period
T, T_0 :	absolute temperature under measurement, resp. reference conditions
U :	polarizing voltage
z :	depth in water
z_{max} :	depth of absorbed dose maximum on the beam central axis
z_{ref} :	reference depth in water, measured along the beam central axis

Appendix 9: List of references

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