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

Recommendations No. 8, Revision 2018

Contents

1. Introduction

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

The structure of these recommendations is as follows: In the chapter "Legal aspects" the main legal points concerning dosimetry are mentioned. In "Recommended ionisation chambers and phantoms" recommendations for the instrumentation are given. In the chapter "Determination of absorbed dose to water" and the appendices 3 to 5 it is described how to determine the dose and how to get the correction factors for that purpose. The uncertainties of these measurements are discussed in chapter 5. In the appendices the calculation of corrections factors and the calibration of a field dosimeter are covered, as well as a description of the calibration procedure at METAS.

The present recommendations are a revised version of the Swiss Society of Radiobiology and Medical Physics (SSRMP) recommendations No. 8, 2000. As the initial recommendations, these recommendations are based on the international guideline of the IAEA [1]. The recommendations comply with the IAEA/WHO/ESTRO code of practice [1]. However, radiation quality correction factors differ between the Swiss protocol and IAEA/WHO/ESTRO code of practice. Additionally this revised version covers the use of flattening filter free beams.

The ranges of radiation qualities covered in this document are

- *^{60}Co gamma radiation*

- *High-energy photons generated by accelerator electrons with nominal energies in the range 4 MeV to 21 MeV.*

The document only covers the determination of dose to water for machines, which can produce a nominal field size of 10 x 10 cm^2 (SSD = 100 cm).

For the dosimetry of high-energy electrons the user should follow the SSRMP recommendations No. 10 [2].

The present recommendations provide only a methodology for the determination of absorbed dose to water in the reference point. The dosimetry at any other point is not in 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 verification 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], the Ordinance of Accelerators of April 26, 2017 [9]. The verification refers more specifically to the general provisions of the Ordinance of Measuring Instruments of February 15, 2006 [7] and to the Ordinance of the Federal Department of Justice and Police (EJPD) for Measurement Devices for Ionizing Radiation (OMDIR) of December 7, 2012 [8].

a Quantities and units

In radiation therapy the quantity of interest is the absorbed dose to water. According to Article 13 of the Ordinance of Units [6], an absorbed dose is measured in Gray (Gy).

b Verification and handling of dosimeters

Two kinds of dosimeters are distinguished:

- reference dosimeter instruments, consisting of an ionisation chamber, an electrometer and a radioactive check source are verified at METAS. A **verification** at METAS includes the determination of the 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 MV beams. The recommended procedure for the calibration of a field dosimeter is a comparison with a reference dosimeter as described in Appendix 1.

  Parts of a reference dosimeter system may be identical with parts of a field dosimeter.

The verification of reference dosimeters is described in OMDIR [8]. The most important points are:

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

- **Handling:** In case the dosimeter is used more than once per half year the user has to check the constancy of it at least half-yearly by means of the radioactive check source, a thermometer and a barometer with calibrations traceable to national standards [8]. In case the dosimeter instrument 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 ± 0.5 % (Appendix 2).

The certified medical physicist is responsible for the checks of the reference dosimeter instruments and the cross-calibration of the field dosimeters [9].

3.   Recommended ionisation chambers and phantoms

As chamber of a reference dosimeter system, thimble-type ionisation chambers with a cavity volume of typically 0.3 to 0.7 cm^3 are recommended. These ionisation chambers with air cavities should not be sealed, so that they are open to the ambient air and in equilibrium with the ambient air pressure.

Water is recommended as phantom material. The phantom should be a full-scatter phantom and should extend at least 5 cm outside the beam edges and at least 10 cm beyond the chamber centre along the beam axis. Recommended is a water phantom of at least 30 x 30 x 30 cm^3.

For ionisation chambers that are not waterproof a close-fitting waterproof plastic cap (made of low-Z materials, e.g. Perspex) should be used. The wall of the cap should be sufficiently thin 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 is then a component of the dosimeter and the calibration coefficients are only valid when the same cap is used during calibration at METAS.

4.   Determination of absorbed dose to water

a   Absorbed dose to water at 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 defined as:

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

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

b   Reference conditions of calibration and conditions of validity of the calibration

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).

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
Radiation quality	^{60}Co
Source to chamber distance	100 cm
Field size	10 cm x 10 cm (50 % isodose) at the centre of the chamber

The conditions of validity are the conditions under which the verification by METAS is valid:

Depths in water	5 g/cm^2 for TPR$_{20,10}$ = 0.570, 10 g/cm^2 for 0.639 < TPR$_{20,10}$ < 0.798
Radiation beam quality index	TPR$_{20,10}$ = 0.570 and TPR$_{20,10}$ = 0.639 - 0.798;

TPR$_{20,10}$ represents the beam quality index for a beam quality Q in high-energy photons
specified by the tissue-phantom ratio

It is recommended to use the same field size as at the calibration, in order to have the same energy spectrum.

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 that for which the calibration coefficient applies (see chapter 4b). The factor k_{Tp} corrects the influence of air temperature and pressure to the air density in the open cavity volume:

$$k_{Tp} = \frac{p_0 \cdot T}{p \cdot T_0} \tag{2}$$

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

Details on how to determine p and T can be found in Appendix 3.

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. On the other hand, for continuous radiation the effect is usually very small. For typical radiation sources at clinical dose rates the correction for ion recombination is therefore usually negligible when using continuous radiation, as from a ^{60}Co irradiation unit. For the measurement of pulsed MV radiation a correction for ion recombination shall be made. In Appendix 4 it is described how to measure or calculate the ion recombination correction factor for a pulsed photon beam.

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,

$$k_f = 1 \tag{3}$$

f   Polarity effect correction k_{pol}

It is mandatory to use the ionisation chamber with the same electrometer and with the same polarising potential as during the calibration at METAS. A polarity effect correction is not needed, because it is already considered in the calibration factor.

$$k_{pol} = 1 \tag{4}$$

g   Correction k_Q for radiation beam quality Q

The radiation beam quality correction factor k_Q can be derived using a double exponential regression function f, which was determined experimentally at METAS (Appendix 6).

$$\boldsymbol{k_Q = f}(\text{TPR20,10}) = \boldsymbol{a \cdot e}^{(\boldsymbol{b \cdot e}^{(\boldsymbol{c} \cdot \text{TPR20,10})})} \tag{5}$$

The values a, b and c are stated in the verification certificate of the dosimetry instrument. $\text{TPR}_{20,10}$ is in these recommendations used as beam quality index to specify the beam quality Q of high energy photons. For determination of $\text{TPR}_{20,10}$ see Appendix 5. This function is only valid for certain types of ionisation chambers and for values of $\text{TPR}_{20,10}$ between 0.639 and 0.798 for flattened and flattening filter-free beams (see Appendix 6). For beams with $\text{TPR}_{20,10}$ outside this range values of k_Q must be taken from the tables provided in TRS 398 [1]. It has been demonstrated that the correlation between k_Q and the stopping power ratio is similar between flattening filter free and flattened beams (accuracy of 0.3 %) [10, 11]. In the case of flattening filter free beams, the magnitude of the volume averaging effect due to the non-flat dose profile needs to be evaluated and potentially corrected for.

5.   Typical uncertainties in absorbed dose determination

The evaluation of uncertainties in the recommendations follows the guidance given by 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 up to the calibration of a reference dosimeter in terms of $N_{W,Q}$ at the verification laboratory (in contrast to the IAEA 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 are shown on the verification certificate. The uncertainties for Step 2 are taken from [12] and they are only valid for 6 - 25 MV (below 6 MV they have to be estimated by the user).

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

Typical standard uncertainties are as follows:	Standard uncertainty ($k=2$)
Step 1: Verification Laboratory	
Calibration factor $N_{W,Q}$	1.8 % (2.1 % for FFF beams [10,11])
Step 2: User's Beam	
Corrected Reading	0.98 %
Establishment of reference conditions	0.94 - 1.24 % (6 - 25MV)
Combined standard uncertainty in $D_{W,Q}$	**2.25 - 2.40 % (2.50 -2.63 % for FFF)**

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 accelerator and the same radiation qualities as will subsequently be measured with the field dosimeter.

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 factor 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 these corrections will cancel.

The calibration factor for the field dosimeter is given by:

$$N_{W,Q}^F = \left[\frac{k_{Tp}^R \, k_S^R \, M^R}{k_{Tp}^F \, k_S^F \, M^F} \right] N_{W,Q}^R \tag{6}$$

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

If the measuring conditions and the dosimetry instruments are identical, then the formula is reduced to:

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

Appendix 2: Radioactive check source measurements

Radioactive check source measurements are performed to control 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 a certain check source 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 it 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 also be allowed after inserting a chamber for it to stabilise and to achieve temperature equilibrium with the check source; about 10 min should normally be sufficient.

The verification of the reference dosimeter expires, if, after correction for air density and the decay of the source, the results differ by more than 0.5 % 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 verified again.

The expected ionisation current of the check source measurement can be calculated:

$$I_e = \frac{I_k}{k_{Tp}} \cdot e^{-\ln(2)\cdot\frac{t}{T_{1/2}}} \tag{8}$$

with:

I_k ionisation current in pA given for the check source currently in the verification certificate

I_e expected ionisation current of the check source measurement

$e^{-\ln(2)\cdot\frac{t}{T_{\frac{1}{2}}}}$ decay factor for the time t elapsed between the verification date and the actual date

$T_{\frac{1}{2}}$ half-life of check source according to the calibration 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 each traceable to national standards have to be used [8].

The temperature T of the air in a chamber should be taken as that of the water phantom, when in equilibrium. Note that due to evaporation the water temperature will usually be up to a degree below the room temperature. The point of temperature measurement should be as close to the cavity volume as possible. To reach the thermal equilibrium between the ionisation chamber and the phantom it takes typically 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 2 % or more in an X-ray beam of a typical hospital linear accelerator.

For pulsed radiation, the ion recombination correction factor k_S depends on the chamber geometry, the applied polarising potential, and the dose per macro pulse [13].

There are different options to determine k_S. It is either possible to calculate k_S for example as described in DIN 6800-2 [14]. Or, ion recombination gives rise to an approximately linear relation between $1/M_N$ and $1/U$ under near saturation conditions ($k_S < 1.05$), where M_N is the non-corrected dosimeter reading (in C) and U the polarising potential. The method of measuring the ion recombination correction is to measure the dosimeter reading (in C) for different (>2) polarising potentials (at least a factor of two between the minimum and maximum voltage) and to plot the function $f : \frac{1}{U} \to \frac{1}{M_N}$. The reading under complete saturation, M_S, is then the inverse of the intercept of a linear plot to the data with the $1/M_N$ axis; i.e. $\lim_{U \to \infty} f\left(\frac{1}{U}\right) = \frac{1}{M_S}$. The corresponding correction factor to apply is then:

$$k_S = \frac{M_S}{M_N} \tag{9}$$

where M_N is the non-corrected dosimeter reading (in C) corresponding to the normally applied polarisation potential.

Appendix 5: Determination of the radiation beam quality index

In these recommendations for high energy photons produced by a clinical linear accelerator the beam quality Q is specified by the tissue-phantom ratio $TPR_{20,10}$ (beam quality index) [1].

There are two different ways to determine the radiation quality index $TPR_{20,10}$. For both methods the field size is 10 cm × 10 cm. The correction of the effective point of measurement can be done, but it is not necessary because its influence is negligible [1].

(i) Constant source to detector distance

The ionisation charges M_{xy} are measured in a water phantom at a constant source to detector distance of 100 cm at the depths of 20 cm and 10 cm. The beam quality index is the ratio of the two readings:

$$TPR_{20,10} = \frac{M_{20cm,80cm}}{M_{10cm,90cm}} \tag{10}$$

(ii) Constant source to surface distance

The ionisation charges M_{xy} are measured in a water phantom at a constant source to surface distance of 100 cm at the depths of 10 cm and 20 cm. The ratio of the two readings is used to further obtain $TPR_{20,10}$ [1, 14]:

$$m = \frac{M_{20cm,100cm}}{M_{10cm,100cm}} \tag{11}$$

and

$$TPR_{20,10} = 1.2661 \cdot m - 0.0595 \tag{12}$$

It is recommended to use ionisation chambers for these measurements and not diodes. Diodes are more sensitive to the low energy part of the photon spectrum and therefore might overestimate the dose in larger depths [14].

In both methods it is assumed that ratios of the readings are an acceptable approximation of ratios of absorbed doses [1], due to the slow variation with depth of the water/air stopping power ratios. It is recommended that the influence of recombination effects in ionisation chambers is investigated at the two depths of measurement, particularly in the case of photon beams operating at high dose per pulse.

Appendix 6: Calibration of a reference dosimeter at METAS

METAS renews typically every 6-7 years its calibration of the absorbed dose to water standard for Cobalt radiation (^{60}Co, half-life 5.27 years) using the water calorimeter primary standard. Additionally, about every 10 years water calorimetry is also done for high energy photon fields that are generated by METAS's electron accelerator in the energy domain between 4 MeV to 21 MeV. Out of these measurements several internal secondary standards are calibrated for both ^{60}Co and high energy photon beams. These secondary standard dosimeters are ionisation chambers of type NE 2571 and NE 2611A read out by Keithley 6517 electrometers. The k_Q values for different chamber types are derived by cross-calibrating them with these secondary standards. Indeed, these measurements are to be performed before a new type of chamber can be calibrated. In the following, the process resp. the metrological traceability is described that is applied for the calibration of an ionisation chamber to be used in reference dosimetry in a radiotherapy center (see Figute 1).
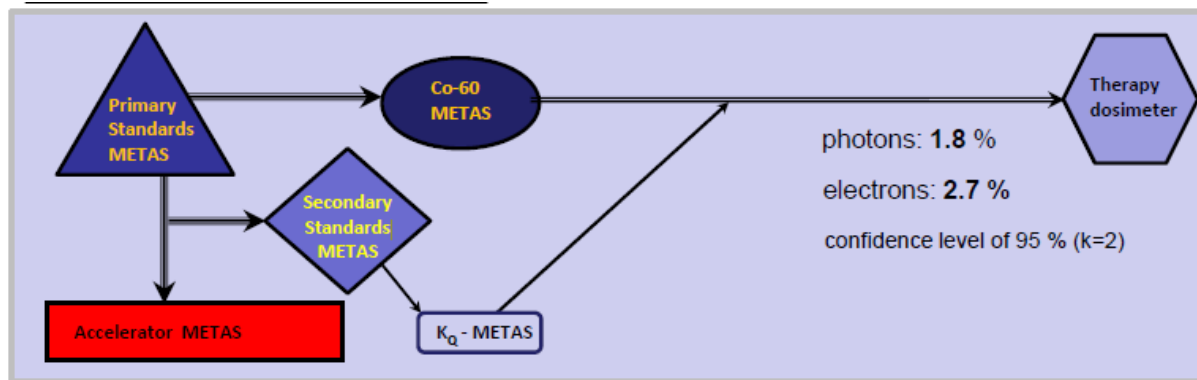
Figure 1: Schematic overview of the metrological traceability in the calibration of the ionisation chamber to be used for reference dosimetry at the radiotherapy center.

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

For the determination of the calibration coefficient N_{W60Co} for the absorbed dose to water in ^{60}Co reference beam the ionisation chamber is irradiated by means of a General Electric Alcyon II type irradiation unit. The dose rate provided by this ^{60}Co source (i.e. absorbed dose to water per minute under reference conditions) was antecedently determined by means of the METAS water calorimeter primary standard.

The calibration coefficient N_{W60Co} is determined for the following reference conditions: A reference plane is defined perpendicularly to the central beam axis of the radiation field at a distance of 1.0 m apart from the focal point of the ^{60}Co source. The axis of the ionisation chamber, which has to be calibrated, coincides with that reference plane. The marked line on the stem of the ionisation chamber is oriented such that it points towards the source. The ionisation chamber, either inherently waterproof or embedded in a water sleeve, is put into 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 amounts 10 x 10 cm^2.

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 $TPR_{20,10}$ and the calibration coefficient determined in ^{60}Co beam. This procedure is applied for several secondary standard ionisation chambers of the same model. This is then repeated at several beam qualities indexes $TPR_{20,10}$ between 0.639 und 0.798. These 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 put into the METAS water phantom such that the effective water depth along the beam path is 10 g/cm^2. Further, the experimental conditions are identical with the conditions applied for the calibration of secondary standards.

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

In the framework of its calibrations provided to the Swiss centres for radiotherapy, METAS has gained extensive data of calibration coefficients for various types of ionisation chambers and radiation qualities. Based on these data, a semi-empirical model was evaluated that uses the relation "$k_Q = a \cdot exp(b \cdot exp(c \cdot Q))$" to predict k_Q as a function of the radiation quality index $TPR_{20,10}$. The parameters *a*, *b* and *c* were fitted to the k_Q-values that were experimentally determined in the accelerator radiation field. The analysis of the mentioned data that was acquired until the year 2008 showed that two sets of fit parameters *a*, *b* and *c* are able to accurately describe k_Q for all ionisation chamber types used so far: One set for the prediction of all PTW Farmer ionisation chamber types and a second set of parameters for three NE type chambers. Although slight differences were observed, for instance, between different types of the same vendor, or between measurements with and without water sleeve, the analysis indeed showed, that this variation can be neglected when compared to statistical scatter of individual determination. Therefore, the use of only two models, one for PTW and one for NE type chambers, was finally agreed. Specifically, data for this determination of k_Q were available for the following ionisation chamber types:

• PTW: 23332, 233641, 30001, 30006, 30012 and 30013
• NE: 2561, 2571 and 2611A

This list covers all ionisation chamber types that have been used so far in reference dosimetry at Swiss radiotherapy centers. If in future other ionisation chamber types will be used in reference dosimetry, the validation of the appropriate model for the prediction of k_Q will have to be done in the course of the approbation process for that (new) chamber type [7,8].

Appendix 7: List of symbols

a, b, c :	values given by the calibration certificate to determine k_Q
$D_{W,Q}$:	absorbed dose to water in radiation quality *Q*
F :	as superscript: field dosimeter
k :	coverage factor of the combined standard uncertainty, usually *k=2*.
k_Q :	correction factor for the radiation quality
k_{Tp} :	air density correction factor
k_S :	ion recombination correction factor
k_f :	correction factor for humidity
k_{pol} :	correction factor for polarity
m :	ratio of ionisation currents at 10 cm depth to that at 20 cm using a constant source-surface distance
M :	non-corrected dosimeter reading
M_{xy}:	non-corrected dosimeter reading a depth *x* and source surface distance *y*
M_Q :	corrected dosimeter reading
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)
I_m :	mean of check source ionisation current (instrument reading, when using the radioactive check source)
M_S :	reading of the dosimeter under complete saturation
$N_{W,Co60}$:	calibration coefficient to convert the instrument reading to absorbed dose to water for photon irradiation of ^{60}Co
$N_{W,Q}$:	calibration coefficient to convert the instrument reading to absorbed dose to water in a radiation beam quality *Q*
p, p_0 :	absolute air pressure under measurement, resp. reference conditions
R :	as superscript: reference dosimeter
r_F :	relative humidity of the air
t :	time elapsed between the reference date of verification and the date of measurement
$T_{\frac{1}{2}}$:	half-life period
T, T_0 :	absolute temperature under measurement, resp. reference conditions
$TPR_{20,10}$:	ratio of absorbed dose at 20 cm depth to that at 10 cm using a constant source-chamber distance; represents the beam quality index for a beam quality Q
U :	polarising potential

Appendix 8: References

[1] Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water, Technical Report Series No. 398, International Atomic Energy Agency, Vienna, 2000. And V. 12 June 2006, most final and corrected version, available at http://www-na-web.iaea.org/nahu/DMRP/documents/CoP_V12_2006-06-05.pdf.

[2] High-Energy Electron Beam Therapy Dosimetry with Ionisation Chambers, SSRMP Recommendations No. 10 (2002).

[3] Quality Control of Medical Electron Accelerators, SSRMP Recommendations No. 11 (2014)

[4] Radiological Protection Act (RPA) SR 814.50, March 22, 1991.

[5] Radiological Protection Ordinance (RPO) SR 814.501, April 26, 2017.

[6] Ordinance of Units, Einheitenverordnung SR 941.202, November 23, 1994.

[7] Ordinance of Measuring Instruments, Messmittelverordnung (MessMV) SR 941.210, February 15, 2006.

[8] Ordinance of the EJPD for Measurement Devices for Ionizing Radiation (OMDIR), Verordnung des EJPD über Messmittel für ionisierende Strahlung (StMmV) SR 941.201.5, December 7, 2012.

[9] Verordnung des EDI über den Strahlenschutz bei medizinischen Teilchenbeschleunigeranlagen (Beschleunigerverordnung, BeV) SR 814.501.513, April 26, 2017

[10] Comparison between the TRS-398 code of practice and the TG-51 dosimetry protocol for flattening filter free beams. Lye, J. E., Butler, D. J., Oliver, C. P., Alves, A., Lehmann, J., Gibbons, F. P., & Williams, I. M. (2016). *Physics in Medicine and Biology*, *61*(14), N362

[11] IPEM topical report 1: guidance on implementing flattening filter free (FFF) radiotherapy. Budgell, G., Brown, K., Cashmore, J., Duane, S., Frame, J., Hardy, M., ... & Thomas, R. (2016). *Physics in Medicine and Biology*, *61*(23), 8360.

[12] Study of the uncertainty in the determination of the absorbed dose to water during external beam radiotherapy calibration, Castro P., Garcia-Vicente F., Minguez C., Floriano A., Sevillano D., Perez L. and Torres J. J., J Appl Clin Med Phys, Jan 22; 9(1) 2676 (2008).

[13] Current collection and ionic recombination in small cylindrical ionization chambers exposed to pulsed radiation, Boag J. W. and Currant J., Br. J. Radiol., **53**(629), 471 (1980).

[14] DIN 6800-2: Dosismessverfahren nach der Sondenmethode für Photonen- und Elektronenstrahlung Part 2, DIN, March 2008.

Appendix 9: Members of the working group:

Helmut Haerle, Kantonsspital Winterthur

Federico Hasenbalg, Stadtspital Triemli

Lukas Hirschi, Stadtspital Triemli

Lisa James, Universitätsspital Bern, Strahlentherapie der Radiologie, München

Götz Kohler, Universitätsspital Basel

Christian Kottler, METAS

Samuel Peters, Kantonsspital St. Gallen

Anton Steiner, METAS Bern

Stephanie Tanadini-Lang, Universitätsspital Zürich, Chair of the working group

Véronique Vallet, Centre Hospitalier Universitaire Vaudois

Lotte Wilke, Universitätsspital Basel, Universitätsspital Zürich