High-Energy

Photon Beam Therapy Dosimetry

with Ionisation Chambers

(Recommendations)

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Index

1   Introduction

The scope of these recommendations „High-Energy Photon Beam Therapy Dosimetry with Ionisation Chambers" is to provide the user with guidelines in order to base his dosimetry on a reference dosimeter system that has been calibrated in absorbed dose to water and verified at the Swiss Federal Office of Metrology (OFMET).

The structure of these recommendations is as follows: In the chapter "Legal aspects" the main legal points concerning dosimetry are mentioned. In "Ionisation chambers, phantoms and waterproof sheaths" recommendations for the instrumentation are given. In the chapter "Determination of the absorbed dose to water" it is described how to determine the dose and how to get the correction factors for that purpose. In the chapter "Calibration of a field dosimeter" recommendations for a calibration of a dosimeter traceable to the national standards are given. The uncertainties of these measurements are discussed in chapter 6.

For the preparation of the present recommendations, it was decided to rely as much as possible on international guidelines, especially those from the International Atomic Energy Agency (IAEA). The recommendations fully comply with the new IAEA/WHO/ESTRO code of practice[1].

The ranges of radiation qualities covered in this document are:

- ^{60}Co gamma radiation
- high-energy photons generated by accelerator electrons with energies in the range 4 MeV to 21 MeV

For the dosimetry of high-energy electrons the user should still follow the Swiss Society of Radiobiology and Medical Physics (SSRMP) recommendations No.4, 1992[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 qualified medical physicist to apply these recommendations in a suitable manner.

2 Legal aspects

Effective are the Radiological Protection Act of March 23, 1991[3], the Radiological Protection Ordinance of June 22, 1994[4], the Ordinance of Units of November 23, 1994[5], and the OFMET Directives for the Reference Dosimeter Systems in Radiotherapy of May 22, 1997[6].

2.1 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, an absorbed dose is measured in Gray (Gy).

2.2 Verification and use of dosimeters

Two kinds of dosimeters are distinguished:
- reference dosimeter systems, consisting of an ionisation chamber, an electrometer and a radioactive check source;
- field dosimeters, which have a similar composition and are used for routine dosimetry.

Parts of a reference dosimeter system may be identical with parts of a field dosimeter. However, it is recommended not to use the ionisation chamber of the reference dosimeter for routine work.

The reference dosimeter system must be verified every 4 years according to the Directives for the Reference Dosimeter Systems in Radiotherapy of the 22nd of May 1997. The competent authority for the verification is OFMET.

The medical physicist is responsible for the checks of the reference dosimeter systems and the calibration of the field dosimeters (Article 74 of the Radiological Protection Ordinance).

The main issues of these directives are: The dosimeter system is calibrated at those radiation qualities, at which it is used. The check source response is measured at calibration. It is verified, if it is possible to calibrate the dosimeter system with an accuracy of ±3% at a confidence level of 95%. The user shall check the constancy of the dosimeter at least half-yearly by means of the radioactive check source, a thermometer and a barometer whose calibration is for both traceable to national standards. These checks shall be documented. The deviation of the result of the check relative to the value given in the verification certificate must be within ±0.5% (see Appendix 4).

The recommended procedure for the calibration of a field dosimeter is a comparison with a reference dosimeter as described in chapter 5.

3   Ionisation chambers, phantoms and waterproof sheaths

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 30x30x30 cm^3.

For ionisation chambers that are not waterproof a close-fitting waterproof plastic sheath, (made of Low-Z materials, e.g. Perspex) should be used. The wall of the sheath 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 sheath should be vented to allow the air pressure in the chamber to reach ambient air pressure quickly. The sheath is then a component of the dosimeter and the calibration factors are only valid when the same sheath is used as at the calibration at OFMET.

4   Determination of the absorbed dose to water

In order to get reliable values 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 4.

4.1   Reference conditions

The reference conditions are those conditions for which the calibration factor $N_{W,Q}$ for absorbed dose to water $D_{W,Q}$ of a dosimeter is specified. The reference conditions to which the verification by OFMET refers are:

Temperature T_0	293.15 K (20°C)
Absolute air pressure p_0	1013.25 hPa
Relative humidity rF	50%
Charge collection efficiency	100%
Voltage and polarity	according to the verification certificate
Radiation quality	Q_C (see table 1 and appendix 1)
Focus chamber distance	100 cm
Field size	10 cm x 10 cm (50% isodose) at the centre of the chamber
Chamber reference point	centre of the cavity volume on the chamber axis[*]

Table 1: Radiation qualities at OFMET

Nominal generation voltage in MV	Radiation quality index Q_C (= $TPR_{20,10}$)	Depth in water (gcm^{-2})
(^{60}Co)	0.570	5
4	0.634	10
6	0.674	10
8	0.717	10
10	0.747	10
12	0.759	10
15	0.762	10
18	0.783	10
21	0.795	10

Remarks:

These radiation qualities are approximations to the averages of the qualities used in Swiss hospitals. The radiation quality with the nominal generation voltage 15 MV is obtained by using a special filter resulting in a low $TPR_{20,10}$ value. This filter has been chosen in order to get a radiation quality index Q_C close to the average of the qualities used in the hospitals of Switzerland.

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[*] This condition differs from previous recommendations (employing the effective point of measurement). It has to be emphasised, however, that this applies only to the absolute measurement at the reference point, not for relative measurements (possibly involving regions of varying dose gradients).

4.2   Absorbed dose to water at the reference depth

The absorbed dose to water at the reference depth in water for the beam quality Q and in absence of the chamber is given by

$$D_{W,Q} = N_{W,Q_C} \cdot k_{Q,Q_C} \cdot M_Q$$

$$M_Q = M \cdot k_{TP} \cdot k_S$$

where:

$D_{W,Q}$: Absorbed dose to water at the radiation quality Q at the position of the centre of the chamber when the chamber and the sheath are replaced by water
k_{TP} : Air density correction
k_S : Ion recombination correction
k_{Q,Q_C} : Correction for a radiation quality Q different from the radiation quality Q_C, at which the dosimeter has been calibrated
N_{W,Q_C} : Calibration factor for the radiation quality Q_C to convert the instrument reading to absorbed dose to water
M_Q : Corrected instrument reading
M : Non-corrected instrument reading

It is recommended to use the dosimeter with the same polarising potential and the same field size as at the calibration. A polarity effect correction is then <u>not</u> needed.

4.2.1 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 factor applies. The factor k_{TP} corrects the influence of air temperature and air pressure to the air density in the open cavity volume:

$$k_{TP} = (p_0 \cdot T) / (p \cdot T_0)$$

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 4.1.

<u>Determination of k_{TP} by measurement of T and p:</u>
The temperature T of the air in a chamber should be taken as that of the water phantom when in equilibrium; the water temperature should be measured, as it will usually be up to a degree below the room temperature due to evaporation. 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. To get a homogeneous temperature distribution, it is recommended to stir the water in the phantom before starting a measurement.

Thermometers and barometers used for these measurements shall have a calibration traceable to national standards.

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 factor applies, is small (< 0.1%) for relative humidities between 20 and 70% and temperatures between 15 and 25°C and can therefore be neglected.

Determination of k_{TP} by use of the radioactive check source:
Another method to get the correction factor for the air density is to measure the check source response before and after the proper measurement and to compare the mean value with the reference value corrected for the decay of the check source.

Then:

$$k_{TP} \;=\; (M_k / M_m) \cdot \exp [-\ln 2 \cdot (t / T_{\frac{1}{2}})]$$

where:
M_k : value given for the check source current in the verification certificate
M_m : mean of the two check source current measurements at the actual date
$\exp[-\ln 2(t/T_{\frac{1}{2}})]$: decay factor for the time t elapsed between the verification and the actual date ($T_{\frac{1}{2}} = 28.7$ years for ^{90}Sr)

This method gives acceptable results only if the temperature in the check source device and the temperature of the water phantom are the same. In case of a temperature difference, a correction factor for the corresponding air density difference has to be applied.

4.2.2   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 rate or the dose per accelerator pulse. In the case of pulsed radiation, especially with scanned beams, the correction factor for recombination becomes rather important. On the other hand, for continuous radiation the effect is usually very small.

The correction for ion recombination is therefore negligible when using continuous radiation, as from a ^{60}Co irradiation unit.

For the measurement of pulsed X-radiation a correction for ion recombination shall be made.

Detailed data about the saturation of an ionisation chamber can be found in its manual.

In appendix 2 it is recommended how to measure the ion recombination correction factor.

In appendix 3 it is recommended how to calculate the ion recombination correction factor.

4.2.3 Correction k_{Q,Q_C} for a non-standard radiation quality Q

If the radiation quality Q of a user beam differs from the radiation quality Q_C (= $TPR_{20,10}$) at which the dosimeter has been calibrated, a correction factor k_{Q,Q_C} should be applied. The correction factor is given in table 2 as a function of the deviation ΔQ of Q from the standard radiation quality Q_C.

Table 2: Correction factors k_{Q,Q_C} for different Q and $\Delta Q = Q - Q_C$

Q_C	Correction factor k_{Q,Q_C} for $\Delta Q =$							
	+0.005	+0.007	+0.01	+0.02	-0.005	-0.007	-0.01	-0.02
0.634	1.000	1.000	0.999	0.999	1.000	1.000	1.001	1.001
0.674	1.000	0.999	0.999	0.998	1.001	1.001	1.001	1.002
0.717	0.999	0.999	0.998	0.996	1.001	1.001	1.002	1.003
0.747	0.999	0.998	0.997	0.994	1.001	1.002	1.003	1.005
0.759	0.998	0.998	0.997	0.993	1.002	1.002	1.003	1.006
0.762	0.998	0.998	0.997	0.993	1.002	1.002	1.003	1.006
0.783	0.998	0.997	0.996	-	1.002	1.003	1.004	-
0.795	0.998	0.997	0.995	-	1.002	1.003	1.005	-

The given correction factors k_{Q,Q_C} are applicable to all chamber types. They have been calculated by G. Stucki, OFMET, using experimental data for the ionisation chamber NE2611 and a general expression for k_{Q,Q_C} (equation 3.5 in ref. 1) for other ionisation chambers.

5 Calibration of a field dosimeter

5.1 Determination of the calibration factor

The recommended procedure for the 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 by the field dosimeter.

2) Measure the quality index for each radiation quality in order to select the reference dosimeter calibration factor to be used.

3) Compare 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 4.1, 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 and the readings repeated.

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

5) Use the same waterproof sheath on the reference chamber (if the reference chamber is not waterproof) as when verified at OFMET; similarly the waterproof sheath 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 4.2. If the chambers are at identical temperatures and pressures these corrections will cancel. (See formula below).

The calibration factor for the field dosimeter is then given by:

$$N^F_{W,Q} = [(k^R_{TP} \cdot k^R_S \cdot M^R) / (k^F_{TP} \cdot k^F_S \cdot M^F)] \cdot N^R_{W,Q_C} \cdot k_{Q,Q_C}$$

where the superscripts R and F stand for reference and field dosimeter respectively.

If the measuring conditions and the types of each dosimeter are identical then the formula is reduced to:

$$N^F_{W,Q} = (M^R / M^F) \cdot N^R_{W,Q_C} \cdot k_{Q,Q_C}$$

5.2 Determination of the check source response

A reference value M^F_k for the field dosimeter has to be determined in the following way:

$$M^F_k = M^F \cdot k_{TP}$$

where:
M^F : check source response of the field chamber
$k_{TP} = (p_0 \cdot T) / (p \cdot T_0)$ (according to chapter 4.2.1)

6 Typical uncertainties in absorbed dose determinations

The evaluation of uncertainties in these 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. 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 uncertainties in quadrature in the various steps yields the combined standard uncertainty for the determination of the absorbed dose to water at the reference point.

The indicated values are standard uncertainties. A measured value and the corresponding uncertainty represent the interval that contains the value of the measured quantity with a probability of 68%.

Typical standard uncertainties are as follows:

		Standard uncertainty
Step 1:	**Verification Laboratory**	
	Calibration factor N_{W,Q_C}	0.9%
Step 2:	**User Beam**	
	Dosimeter Reading (incl. influence quantities) M_Q	0.8%
	Experimental procedure and stability of dosimetry system	0.7%
Combined standard uncertainty in $D_{W,Q}$		**1.4%**

Appendix 1   Radiation quality Q

1   Radiation quality Q

The radiation quality index Q can be determined in two ways:

1.   The source chamber distance is constant

The radiation quality Q is the tissue-to-phantom-ratio $TPR_{20,10}$, which is defined as the ratio of corrected instrument readings with the chamber at 20 and 10 cm depth in a water phantom with a field size of 10 x 10 cm^2 at the chamber centre and a constant source-chamber distance of 100 cm. The instrument readings at the two depths are corrected for any differences in chamber air temperature and pressure, and for ion recombination losses.

$$Q = TPR_{20,10}$$

2.   The source surface distance is constant

M_{10} / M_{20}, which is defined as the ratio of corrected instrument readings with the chamber centre at 10 and 20 cm depth in a water phantom with a field size of 10 x 10 cm^2 at the water surface and a constant source-surface distance of 100 cm, can also be used as radiation quality index. The radiation quality index Q is then given by (DIN 6800-2, 1997)[7]:

$$Q = 2.012 - 1.050 \cdot m + 0.1265 \cdot m^2 + 0.01887 \cdot m^3$$

where m is the ratio M_{10} / M_{20}.

2   Measuring the radiation quality Q

It is recommended not to use diodes but ionisation chambers for the determination of $TPR_{20,10}$ since using diodes may result in a $TPR_{20,10}$ different from that obtained with ionisation chambers. This difference can amount to more than 1%. The instrument readings at the two depths are corrected for any differences in chamber air temperature and pressure, and for ion recombination losses.

Appendix 2   Measuring the ion recombination correction k_S

1   Continuous radiation

The ion recombination correction factor k_S for continuous radiation is depending on the chamber geometry, the applied polarising potential, and the dose rate. The correction is rather small and it is common practice (and even recommended in this paper, see chapter 4.2.2) to ignore ion recombination for continuous radiation, however, the effect can be experimentally determined as follows:

Ion recombination gives rise to an approximately linear relation between 1/M and $1/U^2$ under near saturation conditions ($k_S < 1.05$). M is the instrument reading and U the polarising potential. The method of measuring the ion recombination correction is to measure the ionisation current (or charge) for different polarising potentials and to plot 1/M versus $1/U^2$. 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. The corresponding correction factor to apply is then:

$$k_S = M_S / M$$

where M is the instrument reading corresponding to the normally applied polarisation potential.

2   Pulsed radiation

For pulsed radiation (e. g. from a linear accelerator) the ion recombination correction may amount to 1% or more in an X-ray beam of a typical hospital linear accelerator. It should not be ignored and all readings shall be corrected.

The ion recombination correction factor k_S for pulsed radiation is depending on the chamber geometry, the applied polarising potential, and the dose per macro pulse.

Ion recombination gives rise to an approximately linear relation between 1/M and 1/U under near saturation conditions ($k_S < 1.05$). M is the instrument reading and U the polarising potential. The method of measuring the ion recombination correction is to measure the ionisation current (or charge) for different polarising potentials and to plot 1/M versus 1/U. 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. The corresponding correction factor to apply is then:

$$k_S = M_S / M$$

where M is the instrument reading corresponding to the normally applied polarisation potential.

Appendix 3   Calculating the ion recombination correction k_S

1   Ion recombination correction factor k_S for continuous radiation

The ion recombination correction factor k_S for continuous radiation is depending on the chamber geometry, the applied polarising potential, and the dose rate. The correction is rather small and it is common practice (and even recommended in this paper, see 4.2.2) to ignore ion recombination for continuous radiation, however, the effect can be estimated by means of the following formula:

$$k_S = 1 + 2.4 \cdot \dot{D} \cdot d^4 / U^2$$

where:

$\dot{D}$:   Absorbed dose rate in Gy/s
d :   Effective electrode separation in mm
U :   Polarising potential in V

For plane-parallel chambers the effective electrode separation is the electrode spacing, whereas the effective electrode separation of cylindrical and spherical chambers is given by:

$$d_{zyl} = (R - r) \cdot \{[(R / r + 1)/(R / r - 1)] \cdot [\ln (R / r) / 2]\}^{\frac{1}{2}}$$

$$d_{sp} = (R - r) \cdot [(R / r + 1 + r / R) / 3]^{\frac{1}{2}}$$

where R is the internal radius of the outer electrode and r is the external radius of the inner electrode in mm.

For thimble-type chambers consisting of a cylindrical main volume and a hemispherical section at the tip, the equivalent electrode separation can be calculated applying a weighting with the percentage of the total volume.

2   Ion recombination correction factor k_S for pulsed radiation

For pulsed radiation (e. g. from a linear accelerator) the ion recombination correction may amount to 1% or more in an X-ray beam of a typical hospital linear accelerator. It should not be ignored and all readings shall be corrected.

The ion recombination correction factor k_S for pulsed radiation is depending on the chamber geometry, the applied polarising potential, and the dose per macro pulse. It can be obtained using an analytical expression based on Boag's theory:

$$k_S = 1 + 0.54 \cdot D \cdot d^2 / U$$

where:

D :   Absorbed dose to water per pulse in mGy
d :   Effective electrode separation in mm (see above)
U :   Polarising potential in V

Appendix 4   Radioactive check source measurements

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 fixed geometrical relationship with the ionisation chamber. The radionuclide usually used is ^{90}Sr.

A check source is normally designed for a particular type of chamber. It is often found that the ionisation current from the chamber varies as the chamber is rotated. If this is the case, a mark is usually engraved on the stem of the chamber by the manufacturer and this 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. If the cause of the discrepancy can not be identified and rectified, the dosimeter must be verified again.

Appendix 5　　　　List of symbols

$\dot{D}$　　　　: absorbed dose rate to water

D　　　　: absorbed dose to water per pulse

d　　　　: effective electrode separation

d_{sp}　　　: effective electrode separation of a spherical chamber

d_{zyl}　　　: effective electrode separation of a cylindrical chamber

$D_{W,Q}$　　: absorbed dose to water at the radiation quality Q

F　　　　: as superscript: field dosimeter

k_{Q,Q_C}　　: correction for the radiation quality Q that is different from the radiation quality Q_C at which the chamber has been calibrated

k_{TP}　　　: air density correction

k_S　　　: ion recombination correction

m　　　　: $m = M_{10} / M_{20}$

M　　　　: non-corrected instrument reading

M_Q　　　: corrected instrument reading

M_k　　　: reference value for the check source response (instrument reading, when using the radioactive check source)

M_m　　　: mean of check source response (instrument reading, when using the radioactive check source)

M_S　　　: reading of the instrument under complete saturation

M_{10} / M_{20} : ratio of ionisation currents at 10 cm depth to that at 20 cm using a constant source-surface distance

N_{W,Q_C}　　: calibration factor to convert the instrument reading to absorbed dose to water at the radiation quality Q_C

p, p_0　　: absolute air pressure under measurement, resp. reference conditions

Q　　　　: radiation quality index (corresponds to $TPR_{20,10}$)

Q_C　　　: standard radiation quality at which the dosimeter has been calibrated

r　　　　: external radius of the inner electrode

R　　　　: internal radius of the outer electrode

R　　　　: as superscript: reference dosimeter

rF　　　: 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; for ^{90}Sr it is 28.7 years

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

U　　　　: polarising potential

Appendix 6   List of references

1   IAEA/WHO/ESTRO
     Absorbed Dose Determination in External Beam Radiotherapy Based on Absorbed-Dose-to-Water Standards: An International Code of Practice for Dosimetry, 1999

2   Swiss Society of Radiobiology and Medical Physics
     Dosimetry of High Energy Photon and Electron Beams, Recommendations No 4, 1992

3   Radiological Protection Act, March 23, 1991

4   Radiological Protection Ordinance, June 22, 1994

5   Ordinance of Units, November 23, 1994

6   OFMET
     Directives for the Reference Dosimeter Systems in Radiotherapy, May 22, 1997

7   DIN
     The Standard DIN 6800-2, October 1997: Dosismessverfahren nach der Sondenmethode für Photonen- und Elektronenstrahlung

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