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High-Energy Electron Beam Therapy Dosimetry with Ionisation Chambers

(Recommendations)

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1 Introduction

The scope of these recommendations “High-Energy Electron 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 and Accreditation (METAS).
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 caps" recommendations for the instrumentation are given. The chapter “Beam quality specification” introduces the beam quality specifier and describes its measurement. 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 7.

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

Aside from having its foundation on standards of absorbed dose, the most significant change from current practice [2] is the use of a new reference depth. This depth has been shown to reduce significantly the influence of spectral differences between different accelerators as well as that of electron and photon contamination in clinical electron beams [3]. For simplicity, beam qualities and all factors dependent on beam quality (including the new reference depth) are expressed in terms of half-value depth R_{50} rather than beam energy. This change parallels the longstanding practice in photon dosimetry where beam qualities are expressed in terms of the penetration of the beam.

The range of radiation qualities covered in this document is:

high-energy electron with R_{50} between 1.75 gcm^{-2} and 8.54 gcm^{-2} ($E_0 \approx$ 5.5 MeV to 22.5 MeV).

For the dosimetry of high-energy electrons these recommendations replace the Recommendations No 4, 1992 [2] of the Swiss Society of Radiobiology and Medical Physics (SSRMP).

For the dosimetry of high-energy photon beams the user should refer to Recommendations No 8, 2000 [4] of the SSRMP.

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. The only exception is the determination of the central-axis depth-dose curve (see appendix 1).

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 [5], the Radiological Protection Ordinance of June 22, 1994 [6], the Ordinance on Units of November 23, 1994 [7], and the METAS Directives on the Reference Dosimeter Systems in Radiotherapy, to be updated in 2002 [8].

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 frequent routine work.

The reference dosimeter system must be verified every 4 years according to the METAS Directives [8]. The competent authority for the verification is METAS.
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 reference dosimeter system is calibrated at a set of radiation qualities, such that each user beam quality Q lies between 2 calibrated radiation qualities that are separated by not more than 2 gcm^{-2}. The minimum number of calibration points necessary is then given by the range and number of user beam qualities. The check source response is measured at calibration. A dosimeter is successfully verified if the uncertainties of the calibration factors obtained in the course of the verification measurements are not greater than 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 ±1% (see appendix 2).

The recommended procedure for the calibration of a field dosimeter is a comparison with a reference dosimeter as described in chapter 6.

3 Ionisation chambers, phantoms and waterproof caps

It is generally accepted [9, 10] that well-guarded plane-parallel ionisation chambers such as the Scanditronix NACP-02 or the PTW 34001 Roos design have a negligible perturbation. For a well-guarded plane-parallel ionisation chamber the collecting electrode is surrounded by a guard electrode having a width of not smaller than 1.5 times the cavity height [10]. These chambers are therefore recommended as chambers of a reference dosimeter system, for all beam qualities. The reference point for plane-parallel chambers is taken to be at the centre of the inner surface of the entrance window. This point must 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 gcm^{-2} outside the beam edges and at least 10 gcm^{-2} beyond the chamber centre along the beam axis.

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

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

For ionisation chambers that are not waterproof a close-fitting waterproof plastic cap (made of low-Z materials, e.g. PMMA) should 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 is then a component of the dosimeter and the calibration factors are only valid when the same cap is used as at the calibration at METAS.

4 Beam quality specification

4.1 Choice of beam quality index

For electron beams the beam quality index is the half-value depth in water R_{50}. This is the depth in water (in gcm^{-2}) at which the absorbed dose is 50% of its value at the absorbed-dose maximum, measured with a SSD of 100 cm and a field size at the phantom surface of at least 15 cm x 15 cm for all energies.

4.2 Measurement of beam quality

For all beam qualities the preferred choice of detector for the measurement of R_{50} is a plane-parallel chamber. A water phantom is used. In a vertical beam the direction of scan should be towards the surface to reduce the effect of meniscus formation.
Ion recombination corrections are required at all depth. These may be derived from a reduced set of representative measurements, for example near the surface, the ionisation maximum and the 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 gcm^{-2}) at which the ionisation current is 50% of its maximum value. The half-value depth in terms of absorbed dose, R_{50}, is obtained using [1,11]

$$R_{50} = 1.029\ R_{50,ion} - 0.06\ gcm^{-2}$$

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

5 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 2.

5.1 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 depth z_{ref} is given by [1,2]

$$z_{ref} = 0.6\ R_{50} - 0.1\ \mathrm{gcm}^{-2} \quad (R_{50} \text{ in gcm}^{-2})$$

This depth is close to the depth of the absorbed-dose maximum z_{max} at beam qualities for which $R_{50} < 4$ gcm^{-2} ($E_0 < 10$ MeV). At higher beam qualities it is larger than z_{max}. For a given accelerator, no two reference beams will have the same reference depth. However, the new depth has been shown to significantly reduce machine-to-machine variations in calibration factors [3] and the accuracy gained justifies its use, particularly for plane-parallel chamber types.

The reference conditions to which the verification by METAS 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)
Source surface distance	100 cm
Field size	15 cm x 15 cm at the surface of the phantom
Chamber reference point	at the centre of the inner surface of the chamber window
Position of chamber reference point	at z_{ref}

Table 1: Radiation qualities at METAS

Nominal electron energy [MeV]	Radiation quality index Q_C (= R_{50}) [gcm^{-2}]	z_{ref} [gcm^{-2}]
5.5	1.75	0.95
6.0	1.95	1.07
7.5	2.62	1.47
9.0	3.31	1.89
10.0	3.70	2.12
12.0	4.35	2.51
15.0	5.67	3.30
18.0	6.90	4.04
20.5	7.52	4.41
22.5	8.54	5.02

5.2 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

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

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

where:

$D_{W,Q}$: Absorbed dose to water at the radiation quality Q at the position of the chamber reference point when the chamber and the waterproof cap, where applicable, are replaced by water

k_{TP} : Air density correction

k_S : Ion recombination correction

$N_{W,Q}$: Calibration factor for the radiation quality Q to convert the instrument reading to absorbed dose to water

M_Q : Corrected instrument reading

M : Non-corrected instrument reading

5.2.1 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 for 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 5.1

Determination of k_{TP} by measurement of T and p:

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. Thermal equilibrium between the ionisation chamber and the phantom is reached after 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 a relative humidity between 20% and 70% and a temperature between 15 °C 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:

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

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
$\exp[-\ln 2 \cdot (t / T_{1/2})]$: decay factor for the time t elapsed between the verification and the actual date ($T_{1/2}$ = 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.

5.2.2 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 per accelerator pulse. For pulsed radiation, especially with scanned beams, the correction factor for recombination becomes rather important, therefore a correction for ion recombination shall be made.

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

A measurement method for the determination of the ion recombination correction factor is described in appendix 3.

5.2.3 Polarity effect correction

It is recommended to use the dosimeter with the same polarising voltage as at the verification. No polarity correction should then be applied in the clinic, as this is implicitly included in the calibration factor.

5.2.4 Determination of $N_{W,Q}$ for the radiation quality Q

The calibration factor for the radiation quality Q_C, at which the dosimeter has been calibrated in the course of the verification, is N_{W,Q_C} (as listed in the verification certificate).

If the radiation quality Q of a user beam differs from any radiation quality at which the dosimeter has been calibrated in the course of the verification, a calibration factor $N_{W,Q}$ corresponding to the radiation quality Q must be determined according to the following procedures:

When the number of available calibration factors does not exceed 4, the new calibration factor $N_{W,Q}$ is determined by means of a linear interpolation using the calibration factors of the 2 closest radiation qualities taken from the verification certificate.

When the number of available calibration factors exceeds 4, the new calibration factor $N_{W,Q}$ shall be calculated as follows:

$$N_{W,Q} = a \cdot R_{50}^{3} + b \cdot R_{50}^{2} + c \cdot R_{50} + d$$

The coefficients a, b, c and d are obtained from a least-squares fit to the set of calibration factors taken from the verification certificate.

6 Calibration of a field dosimeter

6.1 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 5.1, but with an appropriate separation of the chamber centres 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 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 5.2. 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:

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

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:

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

6.2 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 5.2.1)

7 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}	1.0%
Step 2:	**User Beam**	
	Dosimeter Reading (incl. influence quantities) M_Q	0.8%
	Experimental procedure and stability of dosimetry system	1.2%
Combined standard uncertainty in $D_{W,Q}$		**1.8%**

Appendix 1 Determination of the absorbed depth-dose distribution from a measurement of the ion depth-dose

The ion depth-dose measured with an ionisation chamber must be converted to the absorbed depth-dose by taking into account the mean energy of the electrons at the point of measurement. The depth-dose measurement with a plane-parallel ionisation chamber along the central axis can be converted to absorbed dose according to the IAEA code of practice [1] (p. 185-186).

Conversion of relative ion depth-dose to relative absorbed depth-dose

$$\mathrm{PDD}(z) \quad M(z) \cdot s_{w,air}(R_{50},z)$$

PDD(z)	percentage absorbed depth-dose at the depth z in water
M(z)	non-corrected instrument reading with the ion chamber at the depth z in water
$s_{w,air}(R_{50},z)$	mass stopping-power ratio water to air as a function of the beam quality R_{50} and the depth z in water

$s_{w,air}(R_{50},z)$ takes into account the dependence of the mass stopping power of the involved substances (air in the ionisation chamber and water as phantom material) on the electron energy and the point of measurement (depth z). Values of $s_{w,air}(R_{50},z)$ are calculated from monoenergetic data and Monte-Carlo simulations [11] and can be taken from the IAEA code of practice [1] (Table 20, p. 99f).

$s_{w,air}(R_{50},z)$ can also be calculated from the following formula (fitted to basic data):

$$s_{w,air}(R_{50},z) = \frac{1.075 - 0.5087 \cdot x + 0.0887 \cdot x^2 - 0.084 \cdot y}{1 - 0.4281 \cdot x + 0.0646 \cdot x^2 + 0.00309 \cdot x^3 - 0.125 \cdot y}$$

where $x = \ln(R_{50})$ and $y = z / R_{50}$ is the relative depth.

The range of the table for $s_{w,air}$ (R_{50},z) is restricted to R_{50} from 1 gcm^{-2} to 20 gcm^{-2} and for the relative depth z/R_{50} from 0.02 to 1.2. The standard deviation for the fit is 0.4%. As in the IAEA code of practice [1] we assume that the perturbation correction is independent of the measuring depth. For a "well guarded" plane-parallel chamber this assumption is justified.

Determination of the absorbed dose for depth z from the absorbed dose in the reference depth z_{ref}

The absorbed dose for the depth z can be determined from the dose in the reference depth z_{ref} and the relative absorbed depth-dose PDD(z):

$$D_{W,Q}(z) = D_{W,Q}(z_{ref}) \cdot \mathrm{PDD}(z) / \mathrm{PDD}(z_{ref})$$

The absorbed dose in dose maximum (z_{max}) is:

$$D_{W,Q}(z_{max}) = D_{W,Q}(z_{ref}) \cdot \mathrm{PDD}(z_{max}) / \mathrm{PDD}(z_{ref})$$

The distribution of the absorbed dose to water can be directly measured with a diamond detector or a semiconductor diode. According to IAEA code of practice [1] (p. 88), for such a situation the depth-dose distribution should be compared with the corresponding distribution gained with an ionisation chamber.

Appendix 2 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 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. The calibration of the thermometer must be traceable to national standards.

Time should also be allowed after mounting a chamber for it to stabilise and to achieve temperature equilibrium with the check source; at least 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 1% 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 3 Measuring the ion recombination correction 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 a high-energy electron 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 voltage and the dose per 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 voltage. The method of measuring the ion recombination correction is to measure the ionisation current (or charge) for different polarising voltages 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 voltage.

Appendix 4 List of symbols

$D_{W,Q}$: absorbed dose to water at the radiation quality Q
E_0 : mean energy of an electron beam at the phantom surface
F : as superscript: field dosimeter
k_{TP} : air density correction
k_S : ion recombination correction
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(z) : non-corrected instrument reading with the ion chamber at the depth z in water
$N_{W,Q}$: calibration factor to convert the instrument reading to absorbed dose to water at the radiation quality Q
N_{W,Q_C} : calibration factor obtained in the course of the verification 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
PDD(z) : percentage absorbed depth-dose at the depth z in water
Q : radiation quality index (corresponds to R_{50})
Q_C : radiation quality at which the reference dosimeter system has been calibrated in the course of the verification
R : as superscript: reference dosimeter
R_{50} : depth in water at which the absorbed dose is 50% of its value at dose maximum
$R_{50,\,ion}$: depth in water at which the ionisation current is 50% of its maximum
rF : relative humidity of the air
SSD : source surface distance
$s_{w,air(R_{50},z)}$: mass stopping-power ratio water to air as a function of the beam quality R_{50} and the depth z in water
t : time elapsed between the reference date of calibration and the date of measurement
t_{win} : thickness of phantom side window
$T_{1/2}$: half-life period; for ^{90}Sr it is 28.7 years
T, T_0 : absolute temperature under measurement, resp. reference conditions
U : polarising voltage
z : depth in water
z_{max} : depth of absorbed dose maximum
z_{ref} : reference depth in water

Appendix 5 List of references

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