Dosimetry and calibration of photon and electron beams with cavity ion chambers

Chapter 13

F.A. Attix, Introduction to Radiological Physics and Radiation Dosimetry

Almond et al., *AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams*, Med. Phys. 26, pp.1847-1870, 1999

McEwen at al., *Addendum to the AAPM's TG-51 protocol*, Med. Phys. 41, pp. 041501-1-20, 2014

Outline

- General considerations
- Calibration of ion chambers
  - For photon beams
  - For electron beams
- Reference dosimetry of photon beams
- Reference dosimetry of electron beams

Introduction

- The success of radiation therapy depends on the accuracy of a prescribed dose delivery
- This necessitates high accuracy in the dosimetry of high-energy photon and electron beams
- Two aspects are involved:
  - proper calibration of the measuring instruments (ionization chamber and electrometer)
  - characterization of clinical beams

Ion chamber calibration

- Ion chamber can serve as an absolute dosimeter if its gas mass is known
- Most of the commercially manufactured ion chambers are not constructed with exactly known sensitive volume, therefore they require calibration
- National laboratories maintain standard ionization chambers and calibrated γ-ray beams
- Regional calibration laboratories (ADCL - Accredited Dosimetry Calibration Laboratories in US) provide calibration services for general-use instruments for a fee

Ion chamber calibration

- Three approaches to ion chamber calibration:
  - Exposure N_x
  - Dose in cavity gas N_{gas} – old TG-21 protocol
  - Absorbed dose in water N_D– new TG-51 protocol
- Beam dosimetry can be done
  - In free space
  - In water phantom (need correction for field perturbation due to chamber insertion)

Ion chamber calibration

- Starting from an ion chamber calibrated free-in-air for one quantity (exposure or air kerma) and transferring this information to obtain another quantity, absorbed dose to water, based on a measurement in a phantom introduces complexity and possible errors
- To overcome these complexities, primary standards laboratories have developed standards for absorbed dose to water in photon beams from ^{60}Co and accelerator beams and these have an uncertainty of 1% or less

TG-51 protocol

- Prescribes a methodology for clinical reference dosimetry
- Applies to photon beams with nominal energies between ^{60}Co and 50 MV, and electron beams with nominal energies between 4 and 50 MeV
- Uses ion chamber calibrated in terms of absorbed dose to water in a ^{60}Co beam
- Sets up certain well-defined reference conditions
- Starting point: an ion chamber with calibration factor directly traceable to national standards of absorbed dose (may be done through ADCL)

General formalism

- Given $N^{Q}_{D,w}$ (in Gy/C or Gy/rdg), the absorbed-dose to water calibration factor for an ion chamber located in a beam of quality Q
- Under reference conditions:

$$D_w^Q = MN_{D,w}^Q \ \ \text{(Gy)}$$

where D^{Q}_{w} is the absorbed dose to water (in Gy) at the point of measurement of the ion chamber when it is absent and M is the fully corrected electrometer reading in coulombs (C) or meter units (rdg)

General formalism: k_Q

- Usually absorbed-dose calibration factors will be obtained for reference conditions in a ^{60}Co beam
- Define the quality conversion factor, k_Q, such that

$$N_{D,w}^Q = k_Q N_{D,w}^{^{60}Co} \ \ \text{(Gy/Cor Gy/rdg)}$$

- The quality conversion factor k_Q is chamber specific
- Using k_Q, gives

$$\boxed{D_w^Q = Mk_Q N_{D,w}^{^{60}Co} \ \ \text{(Gy)}}$$

General formalism: k_Q

- For *photon beams*, the protocol provides values of k_Q for most cylindrical ion chambers used in reference dosimetry (extended list in Addendum to TG-51)
- Plane-parallel chambers are not included because there is insufficient information about wall correction factors in photon beams other than ^{60}Co beams

General formalism: k_Q

- For *electron beams* the quality conversion factor k_Q contains two components:

$$k_Q = P_{gr}^Q k_{R_{50}}$$

- P^{Q}_{gr} is necessary only for cylindrical chambers
  - corrects for the ionization gradient at the measurement point
  - depends on the radius of the chamber cavity and
  - must be measured by the user, the protocol provides a procedure for measuring P^{Q}_{gr} in the user’s electron beam
- k_{R50} is a chamber-specific factor, a function of electron beam quality as specified by R_{50} (depth in water where dose falls off to 50% of maximum dose)

General formalism: k_Q

- The factor k_{R50} is written as the product of:

$$k_{R_{50}} = k'_{R_{50}} k_{ecal}$$

- k_{ecal} is the photon-electron conversion factor (fixed for a given chamber model), it is the value needed to convert $N_{D,w}^{^{60}\text{Co}}$ into $N_{D,w}^{Q_{\text{ecal}}}$, the absorbed-dose calibration factor in an electron beam of quality Q_{ecal}
- k'_{R50}, is the electron beam quality conversion factor, beam quality dependent, and converts $N_{D,w}^{Q_{\text{ecal}}}$ into $N_{D,w}^{Q}$

General formalism

- In an electron beam, the dose is given by

$$\boxed{D_w^Q = MP_{gr}^Q k'_{R_{50}} k_{ecal} N_{D,w}^{^{60}Co} \ \text{(Gy)}}$$

- The reference depth for electron-beam dosimetry is at $d_{\mathrm{ref}} = 0.6R_{50} - 0.1$ cm, which is essentially at the depth of dose maximum for beams with energies <10 MeV but is deeper for higher-energy beams
- At this depth the protocol can make use of stopping-power ratios, accounting for the realistic (not mono-energetic) energy distributions of electron beams

General formalism

- Cylindrical chambers are preferred dosimeters
- The protocol allows and provides data to carry through the above approach using plane-parallel chambers, although there is evidence that minor construction details significantly affect the response of these detectors in ^{60}Co beams, making the measurements or calculations of k_{ecal} more uncertain
- Plane-parallel chambers should be cross calibrated in high-energy electron beams against calibrated cylindrical chambers

General formalism

- To use this formalism one starts by obtaining an absorbed-dose to water calibration factor for an ion chamber in a ^{60}Co beam
- The next step is to determine the quality conversion factor, k_Q, for the chamber being used
  - This step requires characterization of the beam quality Q

Obtaining an absorbed-dose to water calibration factor

- The absorbed-dose calibration factor is defined as

$$N_{D,w}^{^{60}\mathrm{Co}} = \frac{D_w^{^{60}\mathrm{Co}}}{M} \qquad \text{(Gy/C or Gy/rdg)}$$

where $D_w^{^{60}Co}$ is the absorbed dose to water (in Gy) in the calibration laboratory's ^{60}Co beam at the point of measurement of the ion chamber in the absence of the chamber

- It applies under standard environmental conditions of 22 °C, 101.33 kPa, and relative humidity between 20% and 80%, respectively (in the US and Canada)
- It must be traceable to the user's national primary standard for absorbed dose to water

Obtaining an absorbed-dose to water calibration factor

- The ion chamber should be checked for any problems before it is sent for calibration
- The ion chamber and the electrometer with which it is to be used should both be calibrated, possibly as a single unit
- All ranges of the electrometer that are routinely used for clinical reference dosimetry should be calibrated

Chamber waterproofing

- A chamber is calibrated and used clinically in water
- Equivalent waterproofing techniques must be used for measurements in the user's beam and in the calibration laboratory
- If a chamber is not inherently waterproof (preferred method) it requires extra waterproofing sleeves
- A waterproofing sleeve should minimize air gaps near the chamber wall (≤0.2 mm) and should be made of PMMA ≤1 mm thick

Measurement phantoms

- Clinical reference measurements must be performed in a water phantom with dimensions of at least 30 × 30 × 30 cm^3 (non-water phantoms are prohibited)

- If the beam enters through the plastic wall of the water phantom and the wall is >0.2 cm thick, all depths should be scaled to water-equivalent depths by measuring from the outside face of the wall with the phantom full of water and accounting for the wall density

Charge measurement

- The fully corrected charge reading from an ion chamber, M, is given by

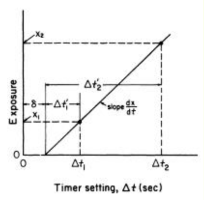
$$M = P_{ion} P_{TP} P_{elec} P_{pol} M_{raw} \quad \text{(C or rdg)}$$

where M_{raw} is the raw ion chamber reading in coulombs, C, or the instrument's reading units (rdg)

  - P_{TP} is the temperature–pressure correction;
  - P_{ion} corrects for incomplete ion collection efficiency
  - P_{pol} corrects for polarity effects
  - P_{elec} takes into account the electrometer's calibration factor if the electrometer and ion chamber are calibrated separately

Shutter timing error – Co-60 only

- Any shutter timing error must be accounted for if needed
- If a beam shutter is used with a timer that closes the shutter when a preset time has elapsed, the Δt measured by the timer may not agree exactly with the $\Delta t'$ representing the shutter-open period



- This can be detected by making two measurements X_1 and X_2 for different timer settings, Δt_1 and Δt_2 and calculating beam shutter timing error:

$$\delta = \frac{X_2 \Delta t_1 - X_1 \Delta t_2}{X_2 - X_1}$$

Polarity corrections

- Polarity effects vary with beam quality and other conditions such as cable position
- It is necessary to correct for these effects each time clinical reference dosimetry is performed
- Taking reading with both polarities applied, M^{+}_{raw} and M^{-}_{raw}

$$P_{\text{pol}} = \left| \frac{\left(M^{+}_{\text{raw}} - M^{-}_{\text{raw}} \right)}{2 M_{\text{raw}}} \right|$$

- M_{raw} (one of M^{+}_{raw} or M^{-}_{raw}) is the reading corresponding to the charge collected for the reference dosimetry measurements in the clinic (should be the same as for the chamber calibration)
- Polarity correction should be less than 0.3% (Addendum to TG-51 allows for 0.4%)

Electrometer correction factor

- If the electrometer is calibrated separately from the ion chamber, the electrometer correction factor, P_{elec}, is just the electrometer calibration factor, correcting the electrometer reading to true coulombs
- It is common practice in the US to calibrate ion chambers and electrometers separately
- It is common practice in Canada to calibrate them as a unit, in which case $P_{\text{elec}} = 1.00$
- Also $P_{\text{elec}} = 1.00$ for cross-calibrated plane-parallel chambers since it cancels out of the final equations

Standard environmental conditions

- Since calibration factors are given for standard environmental conditions of T_0 = 22°C and P_0 = 101.33 kPa (1 atmosphere), one corrects charge or meter readings to standard environmental conditions by

$$P_{\text{TP}} = \frac{273.2 + T}{273.2 + 22.0} \times \frac{101.33}{P}$$

- It is assumed that the relative humidity is always in the range of 20% to 80%, with the reading error ±0.15%
- Chambers require time (usually 5 to 10 min) to reach thermal equilibrium with their surroundings

Corrections for ion-chamber collection inefficiency

- The recombination correction factor P_{ion} is used to correct ion chamber readings for lack of complete collection efficiency
- P_{ion} is a function of the dose per pulse in an accelerator and thus will change if either the pulse rate for a fixed dose rate, or the dose rate is changed
- The correction must be measured in each set of experimental conditions for which clinical reference dosimetry is being performed
- The value of P_{ion} should be less than 1.05

Measuring P_{ion}

- The standard two-voltage techniques should be used: the charge produced by the ion chamber is measured in the beam of interest when two different (by at least a factor of 2) bias voltages are applied
- Let V_H be the normal operating voltage for the detector (always the higher of the two voltages in these measurements), and $M^H{}_{raw}$ be the raw chamber reading
- After measuring $M^H{}_{raw}$ the bias voltage is reduced to V_L, and once the chamber readings have reached equilibrium (takes several minutes), $M^L{}_{raw}$ is measured

Measuring P_{ion}

- Although initial recombination may dominate, for ***continuous*** (i.e., ^{60}Co) beams, the two-voltage formula gives an estimate of the general recombination

$$P_{\mathrm{ion}}(V_H) = \frac{1.-(V_H/V_L)^2}{M^H_{\mathrm{raw}}/M^L_{\mathrm{raw}}-(V_H/V_L)^2}$$

- For ***pulsed*** or pulsed-swept beams with $P_{\mathrm{ion}} < 1.05$

$$P_{\mathrm{ion}}(V_H) = \frac{1.-V_H/V_L}{M^H_{\mathrm{raw}}/M^L_{\mathrm{raw}}-V_H/V_L}$$

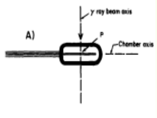
Beam quality specification

- For both photon and electron beams from accelerators, the beam quality must be specified in order to determine the correct value of the quality conversion factor, k_Q or the electron quality conversion factor, k'_{R50}
- For a ^{60}Co beam the factor $k_Q = 1.000$ by definition
- Beam quality must be measured each time clinical reference dosimetry is performed for accelerator beams

Beam quality specification

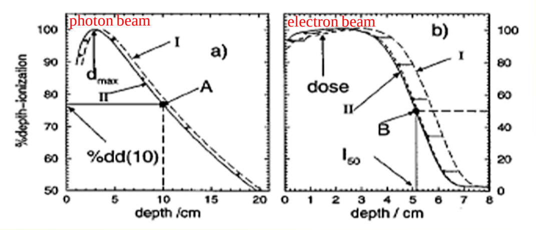
- Beam quality is characterized by a parameter related to the central-axis depth-dose curves for the beam
  - For photons it is %dd(10) – the percentage depth dose at 10 cm depth in water due to photons only
  - For electrons it is R_{50} – the depth in water in cm at which the absorbed dose falls to 50% of the maximum dose
- It is essential to use SSD=100 cm when establishing the beam quality for photon and electron beams because %dd(10) and R_{50} are functions of SSD

Depth of measurement



- The point of measurement for a cylindrical chamber is on the central axis of the chamber and this is always placed at the reference depth when measuring dose at an individual point
- The *effective* point of measurement is upstream of the point of measurement due to the predominantly forward direction of the secondary electrons
- This results in shift of the depth-dose curve upstream (to shallower depth)

Depth of measurement



- Effect of shifting depth-ionization data measured with cylindrical chambers upstream a) by 0.6 r_{cav} for photon beams and b) by 0.5 r_{cav} for electron beams (r_{cav}=1.0 cm). The raw data are shown by curve I (long dashes), shifted data by curve II (solid line). Electron beam curve must be further corrected

Depth of measurement

- For cylindrical and spherical chambers the shift is taken as 0.6r_{cav} for photon beams and 0.5r_{cav} for electron beams, where r_{cav} is the radius of the ionization chamber cavity
- The shifted curves are taken as the depth-ionization curves for cylindrical chambers
- For plane-parallel chambers, the center of the front (upstream) face of the chamber air cavity is the point of measurement, no shift is needed

Depth of measurement

- Using these measurements as depth-ionization curves ignores any variations in P_{ion} and P_{pol} with depth and for electron beams it also ignores any variations in the electron fluence correction factor
- Since well-guarded plane-parallel chambers minimize these variations with depth, they are preferred for measuring electron beam depth-ionization curves

Depth of measurement

- For photon beams the variation in stopping-power ratio is negligible past d_{max} (<0.1%) and thus the depth-ionization curve is treated as a depth-dose curve
  - These same techniques should be used to determine any clinical photon beam depth-dose curve
- In order to determine depth-dose curves for electron beams, the depth-ionization curve must be further corrected for the significant change in the stopping-power ratio with depth
  - This conversion is not needed in the protocol except to transfer the dose from d_{ref} to d_{max} if necessary

Depth of measurement

- In contrast to the depth-dose curve measurement, for measurements of absolute dose at the reference depth in both electron and photon beams, a cylindrical chamber's point of measurement is placed at the referenced depth (10 cm for photons and d_{ref} for electrons)
- The gradient effects are included implicitly in the beam quality conversion factor k_Q for photons and explicitly by the term P^Q_{gr} for electrons

Beam-quality specification for photon beams

- The percentage depth dose at 10 cm depth in a water phantom due to photons only, %$dd(10)_{\text{X}}$, is defined for a field size of 10×10 cm^2 at the phantom surface at an SSD of 100 cm
- At higher energies (about 10 MV and above), the electrons from the accelerator head may significantly affect this dose
- Placing a 1 mm thick lead foil below the accelerator head (about 50 cm from the phantom surface) reduces the electrons contamination to a negligible level, thus %$dd(10)_{\text{Pb}}$ is obtained

Beam-quality specification for photon beams

- For beams with energies less than 10 MV, with %dd(10)<75% the value of %*dd*(10) measured in the open beam is the beam quality, $\%dd(10)_X$
- For beam energies of 10 MV and above (all FFF beams according to the Addendum), the value of $\%dd(10)_X$ for the open beam is obtained from $\%dd(10)_{Pb}$ parameter:

$$\%dd(10)_X = [0.8905 + 0.00150\%dd(10)_{Pb}]\%dd(10)_{Pb}$$

$$[\text{foil at 50 cm, } \%dd(10)_{Pb} \geq 73\%]$$

- If $\%dd(10)_{Pb}$ is less than the thresholds given in the equations, then $\%dd(10)_x = \%dd(10)_{Pb}$

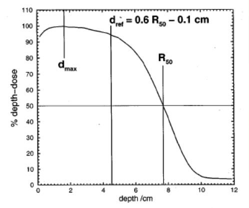
Beam-quality specification for photon beams

- Alternative formula to correct for electron contamination for higher energy beams (up to %*dd(10)*=89%):

$$\%dd(10)_x = 1.267\%dd(10) - 20.0$$

- Here %*dd(10)* is measured for an open beam
- Leads to an error in k_Q of ~0.25%
- The Addendum advocates use of this formula in place of Pb: “Although TG-51 clearly states that the foil must be removed for the dose measurement step, there is anecdotal evidence of confusion as to when the lead foil must be used”

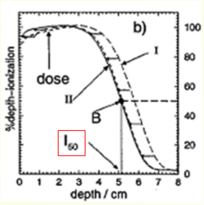
Beam-quality specification for electron beams



- For the purposes of reference beam dosimetry, beam quality in electron beams is specified by R_{50}, the depth in water (in cm) at which the absorbed dose falls to 50% of the maximum dose for a beam, which has a field size on the phantom surface ≥10×10 cm^2 (≥20×20 cm^2 for R_{50} > 8.5 cm, i.e., E > 20 MeV) at an SSD of 100 cm

Beam-quality specification for electron beams

- To determine R_{50} one must first measure a central-axis depth-ionization curve in a water phantom at an SSD of 100 cm



- For cylindrical chambers, correct for gradient effects by shifting the curve upstream by $0.5r_{cav}$
- Next, locate point B at the level of 50% of the maximum ionization; the depth of point B gives I_{50}

Beam-quality specification for electron beams

- The beam quality specifier for the electron beam, R_{50}, is determined from measured I_{50} using

$$R_{50} = 1.029 I_{50} - 0.06 \quad \text{(cm)} \quad (\text{for } 2 \leq I_{50} \leq 10 \text{ cm})$$

or

$$R_{50} = 1.059 I_{50} - 0.37 \quad \text{(cm)} \quad (\text{for } I_{50} > 10 \text{ cm})$$

Photon beam dosimetry

- In photon beams

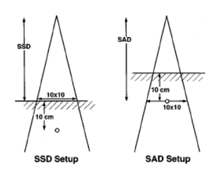
$$\boxed{D_w^Q = M k_Q N_{D,w}^{^{60}Co} \ \text{(Gy)}}$$

gives *the absorbed dose to water under reference conditions*

- Reference dosimetry for photon beams is performed in an *open* beam (i.e., without trays, wedges, or blocks) with the point of measurement of the cylindrical ion chamber placed at the reference depth which is a water-equivalent depth of 10 cm in a water phantom

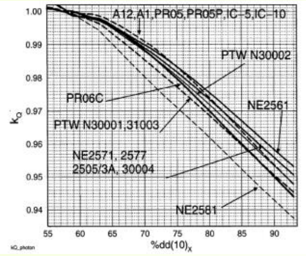
Reference conditions

- Either and SSD or an SAD setup can be used, the field size is 10×10 cm^2
- When using an SSD setup, the field size is defined at the surface of the phantom



- When an SAD setup is being used, the field size is defined at the detector position which is placed at 10 cm depth at the isocenter of the machine

Absorbed dose to water in clinical photon beams: k_Q



- Calculated values of k_Q in accelerator beams as a function of $\%dd(10)_X$ for cylindrical ion chambers commonly used for reference dosimetry
- For ^{60}Co beams k_Q=1.000

Absorbed dose to water in clinical photon beams: k_Q

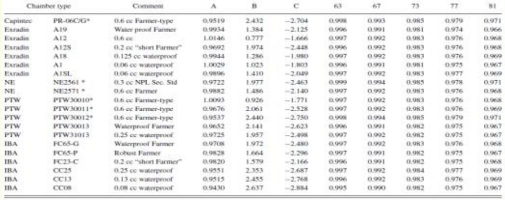


TABLE I. Recommended k_Q fitting parameters and factors as a function of the beam-quality specifier, $\%dd(10)_X$. These parameter values are taken from Monte Carlo calculations of Muir and Rogers (Ref. 21) and Muir *et al.* (Ref. 30) and are valid for $63 < \%dd(10)_X < 86$. Tabulated k_Q values are given for the most common beams (according to the RPC). Users are referred to the manufacturers' data sheets for the specifications of the chambers listed here (wall material and thickness, central electrode, etc.). Chambers requiring a waterproof sleeve were modeled with a 1 mm PMMA sleeve and are indicated below with a *.

Table from Addendum

Chamber type		Comment	Fitting parameters for Eq. (1) ($63 < \%dd(10)_X < 86$)			k_Q values for the most common beams (as function of beam-quality specifier $\%dd(10)_X$)				
			A	B	C	63	67	73	77	81
Capintec	PR-06C/G*	0.6 cc Farmer-type	0.9519	2.432	−2.704	0.998	0.993	0.985	0.979	0.971
Exradin	A19	Water proof Farmer	0.9934	1.384	−2.125	0.996	0.991	0.981	0.974	0.966
Exradin	A12	0.6 cc	1.0146	0.777	−1.666	0.997	0.992	0.983	0.976	0.968
Exradin	A12S	0.2 cc "short Farmer"	0.9692	1.974	−2.448	0.996	0.992	0.983	0.976	0.968
Exradin	A18	0.125 cc waterproof	0.9944	1.286	−1.980	0.997	0.992	0.983	0.976	0.969
Exradin	A1	0.06 cc waterproof	1.0029	1.023	−1.803	0.996	0.991	0.981	0.975	0.967
Exradin	A1SL	0.06 cc waterproof	0.9896	1.410	−2.049	0.997	0.992	0.983	0.977	0.969
NE	NE2561 *	0.3 cc NPL Sec. Std	0.9722	1.977	−2.463	0.999	0.994	0.985	0.978	0.971
NE	NE2571 *	0.6 cc Farmer	0.9882	1.486	−2.140	0.997	0.992	0.983	0.976	0.968
PTW	PTW30010*	0.6 cc Farmer-type	1.0093	0.926	−1.771	0.997	0.992	0.983	0.976	0.968
PTW	PTW30011*	0.6 cc Farmer-type	0.9676	2.061	−2.528	0.997	0.992	0.983	0.976	0.969
PTW	PTW30012*	0.6 cc Farmer-type	0.9537	2.440	−2.750	0.998	0.994	0.985	0.979	0.971
PTW	PTW30013	Waterproof Farmer	0.9652	2.141	−2.623	0.996	0.991	0.982	0.975	0.967
PTW	PTW31013	0.25 cc waterproof	0.9725	1.957	−2.498	0.997	0.992	0.982	0.975	0.967
IBA	FC65-G	Waterproof Farmer	0.9708	1.972	−2.480	0.997	0.992	0.983	0.976	0.968
IBA	FC65-P	Robust Farmer	0.9828	1.664	−2.296	0.997	0.991	0.982	0.975	0.967
IBA	FC23-C	0.2 cc "short Farmer"	0.9820	1.579	−2.166	0.996	0.991	0.982	0.975	0.968
IBA	CC25	0.25 cc waterproof	0.9551	2.353	−2.687	0.997	0.992	0.984	0.977	0.969
IBA	CC13	0.13 cc waterproof	0.9515	2.455	−2.768	0.996	0.992	0.983	0.976	0.969
IBA	CC08	0.08 cc waterproof	0.9430	2.637	−2.884	0.995	0.990	0.982	0.975	0.967

- The table contains values for cylindrical chambers currently manufactured
- Plane-parallel chambers are not included due to insufficient information on wall corrections in photon beams other than ^{60}Co

Absorbed dose at other depths in clinical photon beams

- Clinical reference dosimetry determines the absorbed dose to water at 10 cm depth
- If this is not the reference depth used for clinical dosimetry calculations, one determines the corresponding dose at the appropriate depth
- For SSD setups the clinical percentage depth-dose curves are used
- For SAD setups the clinical tissue-phantom ratio (TPR) curves are used

Electron beam dosimetry

- In electron beam

$$\boxed{D_w^Q = MP_{gr}^Q k'_{R_{50}} k_{ecal} N_{D,w}^{^{60}Co} \quad \text{(Gy)}}$$

gives *the absorbed dose to water under reference conditions* for the same number of monitor units as used to measure the charge *M*, at the point of measurement of the ion chamber, in an electron beam of quality *Q*, specified by R_{50}

Electron beam dosimetry

- For electron beams with $R_{50} \leq 4.3$ cm (incident energies of 10 MeV or less), well-guarded plane-parallel chambers are preferred and they may be used at higher energies
- Plane-parallel chambers must be used for beams with $R_{50} \leq 2.6$ cm (incident energies of 6 MeV or less)

Reference conditions

- Clinical reference dosimetry for electron beams is performed in an *open* beam at the reference depth which is at a water-equivalent depth of

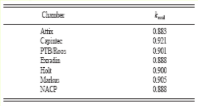
$$d_{\mathrm{ref}} = 0.6R_{50} - 0.1 \quad \text{(cm)}$$

- The point of measurement of the ion chamber is placed at d_{ref}
- For beams with $R_{50} \leq 8.5$ cm, the field size is ≥10×10 cm^2 at the phantom surface and for higher-energy beams it is ≥20×20 cm^2
- SSD may be from 90 to 110 cm (range where stopping –power ratios are not affected)

Absorbed dose to water in clinical electron beams

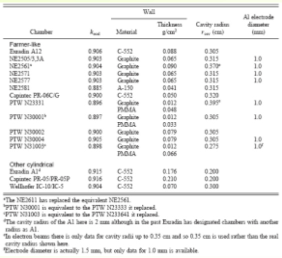
- To calculate the absorbed dose one needs the values of the factors P^{Q}_{gr}, k'_{R50}, and k_{ecal}
- The values of k_{ecal} , a photon-electron conversion factor, for a number of ion chambers are given in tables II and III of the protocol
- The selection of the beam quality Q_{ecal} is arbitrary and has been taken as R_{50} = 7.5 cm for the purposes of the protocol

Absorbed dose to water in clinical electron beams: $\mathbf{k_{ecal}}$



Chamber	k_{ecal}
Attix	0.883
Capintec	0.921
PTB/Roos	0.901
Exradin	0.888
Holt	0.900
Markus	0.905
NACP	0.888

Table II. Plane-parallel chambers



Chamber	k_{ecal}	Wall		Cavity radius r_{cav} (cm)	Al electrode diameter (mm)
		Material	Thickness g/cm^2		
Farmer-like					
Exradin A12	0.906	C-552	0.088	0.305	
NE2505/3,3A	0.903	Graphite	0.065	0.315	1.0
NE2561[a]	0.904	Graphite	0.090	0.370[e]	1.0
NE2571	0.903	Graphite	0.065	0.315	1.0
NE2577	0.903	Graphite	0.065	0.315	1.0
NE2581	0.885	A-150	0.041	0.315	
Capintec PR-06C/G	0.900	C-552	0.050	0.320	
PTW N23331	0.896	Graphite	0.012	0.395[e]	1.0
		PMMA	0.048		
PTW N30001[b]	0.897	Graphite	0.012	0.305	1.0
		PMMA	0.033		
PTW N30002	0.900	Graphite	0.079	0.305	
PTW N30004	0.905	Graphite	0.079	0.305	1.0
PTW N31003[c]	0.898	Graphite	0.012	0.275	1.0[f]
		PMMA	0.066		
Other cylindrical					
Exradin A1[d]	0.915	C-552	0.176	0.200	
Capintec PR-05/PR-05P	0.916	C-552	0.210	0.200	
Wellhofer IC-10/IC-5	0.904	C-552	0.070	0.300	

[a] The NE2611 has replaced the equivalent NE2561.

[b] PTW N30001 is equivalent to the PTW N23333 it replaced.

[c] PTW N31003 is equivalent to the PTW N233641 it replaced.

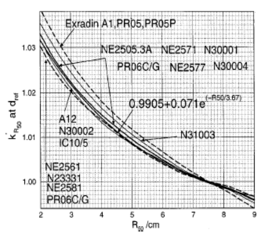
[d] The cavity radius of the A1 here is 2 mm although in the past Exradin has designated chambers with another radius as A1.

[e] In electron beams there is only data for cavity radii up to 0.35 cm and so 0.35 cm is used rather than the real cavity radius shown here.

[f] Electrode diameter is actually 1.5 mm, but only data for 1.0 mm is available.

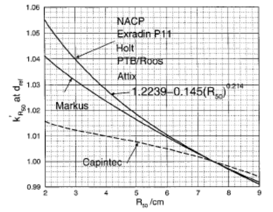
Table III. Cylindrical chambers

Absorbed dose to water in clinical electron beams: $\boldsymbol{k'_{R50}}$



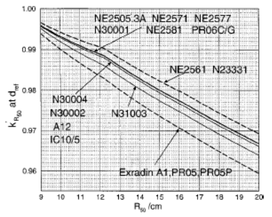
- k'_{R50} – electron beam quality conversion factor
- Calculated values for k'_{R50} as a function of R_{50} for cylindrical ion chambers used for clinical reference dosimetry in electron beams

Absorbed dose to water in clinical electron beams: $\boldsymbol{k'_{R50}}$



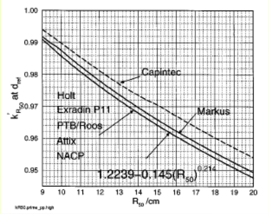
- Calculated values of k'_{R50} at d_{ref} as a function of R_{50} for several common plane-parallel chambers

Absorbed dose to water in clinical electron beams: $\boldsymbol{k'_{R50}}$



- Calculated values of k'_{R50} at d_{ref} for high-energy electron beams as a function of R_{50} for several common cylindrical chambers

Absorbed dose to water in clinical electron beams: k'_{R50}



- Calculated values of k'_{R50} at d_{ref} for high-energy electron beams as a function of R_{50} for several common plane-parallel chambers

Absorbed dose to water in clinical electron beams

- For Farmer-like cylindrical chambers the following expression can be used for $2 \le R_{50} \le 9$ cm with a maximum error of 0.2%:

$$k'_{R_{50}}\,(\text{cyl}) = 0.9905 + 0.0710 e^{(-R_{50}/3.67)}$$

- For well-guarded plane-parallel chambers, the following expression is an analytical representation of the curve shown in the figures, i.e., for $2 \le R_{50} \le 20$ cm:

$$k'_{R_{50}}\,(\text{pp}) = 1.2239 - 0.145\left(R_{50}\right)^{0.214}$$

Absorbed dose to water in clinical electron beams

- The correction for gradient effects (i.e., P^{Q}_{gr}) is not necessary for plane-parallel chambers and is close to unity for cylindrical chambers when the reference depth is at d_{max}, which is usually the case for electron beams below 10 MeV
- For cylindrical chambers P^{Q}_{gr} is determined as

$$P^{Q}_{gr} = \frac{M_{\text{raw}}\left(d_{\text{ref}} + 0.5 r_{\text{cav}}\right)}{M_{\text{raw}}\left(d_{\text{ref}}\right)} \qquad \text{(for cylindrical chambers)}$$

Use of plane-parallel chambers

- For electron beam dosimetry the protocol allows for the use of plane-parallel chambers calibrated in a ^{60}Co beam
- However, since the ^{60}Co calibration factors of at least some plane-parallel chambers appear to be very sensitive to small features of their construction, it is recommended that plane-parallel chambers be calibrated against cylindrical chambers in a high-energy electron beam

Use of plane-parallel chambers

- After determining the beam quality and the reference depth in the high-energy electron beam to be used, measurements are made, in sequence, with the point of measurement of both the calibrated cylindrical chamber and the plane-parallel chamber at d_{ref}
- While measuring with the cylindrical chamber, P^{Q}_{gr} is measured as described above

Use of plane-parallel chambers

- From these measurements the product of $k_{\text{ecal}} N^{^{60}\text{Co}}_{D,w}$ is determined for the plane parallel chamber as

$$\left(k_{\text{ecal}} N^{^{60}\text{Co}}_{D,w}\right)^{\text{pp}} = \frac{\left(D_w\right)^{\text{cyl}}}{\left(M k'_{R_{50}}\right)^{\text{pp}}} = \frac{\left(M P^{Q}_{gr} k'_{R_{50}} k_{\text{ecal}} N^{^{60}\text{Co}}_{D,w}\right)^{\text{cyl}}}{\left(M k'_{R_{50}}\right)^{\text{pp}}} \quad \text{(Gy/C)}$$

- Use of this product circumvents the need for obtaining the ^{60}Co absorbed-dose calibration factor for the plane-parallel chamber

Absorbed dose at $d_{\max}$ in clinical electron beams

- This protocol provides the reference dose at a depth of d_{ref} which, for higher-energy beams, will not be at d_{max} where clinical normalization most often takes place
- To establish the dose at $d_{\max}$ one should use the clinical percentage depth-dose data for a given beam and determine the dose at $d_{\max}$ from that at d_{ref}
- Methods for measuring electron-beam percentage depth-dose curves are given in the AAPM TG-25 protocol

Using other ion chambers

- The protocol provides k_Q data for the majority of chambers used in clinical reference dosimetry in North America
- Other cylindrical chambers can be used by finding the closest matching chamber for which data are given
- The critical features are, in order, the wall material, the radius of the air cavity, the presence of an aluminum electrode, and the wall thickness
- As long as the wall material is matched and the chamber is ‘‘normal,’’ these matching data should be accurate to within 0.5%.

Reference class ion chambers

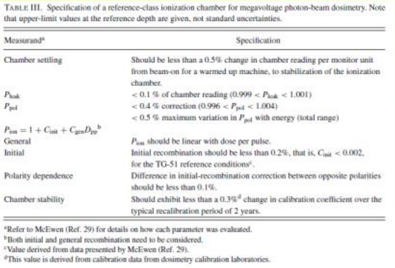


TABLE III. Specification of a reference-class ionization chamber for megavoltage photon-beam dosimetry. Note that upper-limit values at the reference depth are given, not standard uncertainties.

Measurand[a]	Specification
Chamber settling	Should be less than a 0.5% change in chamber reading per monitor unit from beam-on for a warmed up machine, to stabilization of the ionization chamber.
P_{leak}	< 0.1 % of chamber reading ($0.999 < P_{\text{leak}} < 1.001$)
P_{pol}	< 0.4 % correction ($0.996 < P_{\text{pol}} < 1.004$) < 0.5 % maximum variation in P_{pol} with energy (total range)
$P_{\text{ion}} = 1 + C_{\text{init}} + C_{\text{gen}} D_{\text{pp}}$[b]	
General	P_{ion} should be linear with dose per pulse.
Initial	Initial recombination should be less than 0.2%, that is, $C_{\text{init}} < 0.002$, for the TG-51 reference conditions[c].
Polarity dependence	Difference in initial-recombination correction between opposite polarities should be less than 0.1%.
Chamber stability	Should exhibit less than a 0.3%[d] change in calibration coefficient over the typical recalibration period of 2 years.

[a] Refer to McEwen (Ref. 29) for details on how each parameter was evaluated.
[b] Both initial and general recombination need to be considered.
[c] Value derived from data presented by McEwen (Ref. 29).
[d] This value is derived from calibration data from dosimetry calibration laboratories.

Appendix A of the Addendum

TG-51 worksheets

The protocol provides four worksheets:

A. Photon Beams
B. Electron Beams – Cylindrical Chambers
C. $k_{\text{ecal}} N_{D,w}^{^{60}\text{Co}}$ for plane-parallel chambers
D. Electron Beams using Plane-Parallel Chambers

Summary

- Ion chamber calibration: absorbed dose to water calibration factors in TG-51 protocol
- Reference conditions
- Reference dosimetry of photon beams

$$D_w^Q = M k_Q N_{D,w}^{^{60}Co} \quad \text{(Gy)}$$

- Reference dosimetry of electron beams

$$D_w^Q = M P_{gr}^Q k'_{R_{50}} k_{ecal} N_{D,w}^{^{60}Co} \quad \text{(Gy)}$$

General formalism