Chapter 7

Review of TG-51 Protocol

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1. Introduction

During the last three decades, the major emphasis in primary standards laboratories around the world has shifted from standards for exposure or air kerma to those for absorbed dose to water. The rationale is to establish a better basis for dosimetry that relates directly to the quantity of interest in the clinic, absorbed dose to water. Task Group 51 (TG-51) of the Radiation Therapy Committee of the AAPM has published a protocol for the calibration of high-energy photon and electron beams used in radiation therapy (Almond et al. 1999). The formalism and the dosimetry procedures recommended in this protocol are based on the use of an ionization chamber calibrated in terms of absorbed dose to water in a standards laboratory's reference quality ^{60}Co gamma ray beam. The International Atomic Energy Agency (IAEA) has also published a Code of Practice for the calibration of high-energy photon and electron beams (Andreo et al. 2000). This Code of Practice is based on radiation metrology standards of absorbed dose to water and provides a systematic and internationally unified approach for the determination of absorbed dose to water under reference conditions, or beam calibrations, with most kinds of radiotherapy beams. The physics of photon and electron beam dosimetry considered in these two protocols is virtually identical except for beam quality specification in photon beams and the values for gradient corrections in photon beams. This chapter will provide a review of the recommendations given in the TG-51 protocol. The discussion will include, but is not limited to, the use of cylindrical and plane-parallel ionization chambers and techniques for the measurements of beam quality and absorbed dose to water for both photon and electron beams. Information will be provided on the following topics:

(1) the basic equations given in TG-51 for the determination of absorbed dose to water in the user beam quality;

(2) measuring percent depth-ionization and depth-dose curves for photon and electron beams using cylindrical and plane-parallel ionization chambers;

(3) determining the beam quality conversion factor k_Q for photon beams and the electron beam quality conversion factor $k'_{R_{50}}$ for electron beams;

(4) measuring gradient correction factor P_{gr}^{Q} for cylindrical chambers in electron beams;

(5) measuring various correction factors to the charge reading;

(6) using cylindrical and plane-parallel ionization chambers for absolute calibration measurements;

(7) determining dose at the depth of dose maximum from measurements made at the reference depth for both photon and electron beams; and

(8) clarifying potential sources of confusion in the clinical implementation of TG-51 protocol.

2. Formulation

According to the recommendations of the TG-51 protocol, the absorbed dose to water at the reference depth in water, in a beam of quality Q and in the absence of the chamber, is given by

$$D_w^Q = Mk_Q N_{D,w}^{^{60}Co}, \qquad [\mathrm{Gy}] \tag{7.1}$$

where M is the reading of the dosimeter with the **"point of measurement"** of the chamber positioned at the reference depth under reference conditions and corrected for ion recombination, polarity effect, electrometer correction factor, and the standard environmental conditions of temperature, pressure, and relative humidity of the air in the ion chamber. k_Q is a chamber-specific factor which corrects for the effects of the difference between the calibration quality ^{60}Co and the actual user quality Q. $N_{D,w}^{^{60}Co}$ is the absorbed dose-to-water calibration coefficient of the user ionization chamber in a reference quality ^{60}Co beam. The phrase **"point of measurement"** of the cylindrical chamber refers to the center of the cavity volume of the chamber on the chamber axis. For plane-parallel chamber types it refers to the inner surface of the entrance window, at the center of the window.

The tabulated beam quality conversion factors k_Q were calculated as

$$k_Q = \frac{\left[\left(\bar{L}/\rho\right)_{air}^{w} P_{gr} P_{fl} P_{wall} P_{cel}\right]_Q}{\left[\left(\bar{L}/\rho\right)_{air}^{w} P_{gr} P_{fl} P_{wall} P_{cel}\right]_{^{60}Co}}, \tag{7.2}$$

where: $\left(\bar{L}/\rho\right)_{air}^{w}$ is the water-to-air stopping-power ratio; $P_{repl} = P_{gr}P_{fl}$. The gradient correction factor P_{gr} accounts for the fact that a cylindrical chamber cavity with its center at the reference depth samples the electron fluence at a point that is closer to the radiation source than the reference depth. This correction factor depends on the inner radius of the cavity, r_{cav}. The cavity correction P_{fl} corrects for the perturbation of the electron fluence due to scattering differences between the air cavity and the medium. The factor P_{wall} accounts for the differences in the photon mass energy-absorption coefficients and electron stopping powers of the chamber wall material and the medium. For cylindrical chamber types, P_{cel} corrects for the presence of an aluminum central electrode, if there is one.

For electron beams, k_Q is the product of three factors, i.e., $k_Q = P_{gr}^Q k'_{R_{50}} k_{ecal}$, where P_{gr}^Q corrects for the gradient effects at the reference depth when a cylindrical chamber is used in an electron beam; P_{gr}^Q depends on the ionization gradient at the point of measurement. The photon-electron conversion factor k_{ecal} is fixed for a given chamber model and converts absorbed dose-to-water calibration coefficient at ^{60}Co, $N_{D,w}^{^{60}Co}$, into $N_{D,w}^{Q_{ecal}}$, where $N_{D,w}^{Q_{ecal}}$ is the absorbed dose-to-water calibration coefficient in an arbitrary electron beam of quality Q_{ecal}. Tabulated values of k_{ecal} were calculated by:

$$k_{ecal} = \frac{\left[\left(\bar{L}/\rho\right)^{w}_{air} P_{fl} P_{wall} P_{cel}\right]_{Q_{ecal}}}{\left[\left(\bar{L}/\rho\right)^{w}_{air} P_{gr} P_{fl} P_{wall} P_{cel}\right]_{^{60}Co}}. \qquad (7.3)$$

The electron quality conversion factor $k'_{R_{50}}$ is needed to convert $N^{Q_{ecal}}_{D,w}$ into $N^{Q}_{D,w}$ for any beam of quality Q. Tabulated values of $k'_{R_{50}}$ were calculated by

$$k'_{R_{50}} = \frac{\left[\left(\bar{L}/\rho\right)^{w}_{air} P_{fl} P_{wall} P_{cel}\right]_{Q}}{\left[\left(\bar{L}/\rho\right)^{w}_{air} P_{fl} P_{wall} P_{cel}\right]_{Q_{ecal}}}. \qquad (7.4)$$

Thus, for an electron beam, equation (7.1) becomes

$$D^{Q}_{w} = M P^{Q}_{gr} k'_{R_{50}} k_{ecal} N^{^{60}Co}_{D,w}. \qquad \text{[Gy]} \qquad (7.5)$$

One of the advantages of expressing k_Q as a product of three terms is that the chamber-to-chamber variation of $k'_{R_{50}}$ is the same for all well-guarded plane-parallel chambers. For cylindrical chambers, the variation in $k'_{R_{50}}$ is much smaller than the corresponding variation that would be obtained if equation (7.2) were used for the calculation of k_Q. Note that the factors in equation (7.2) need to be evaluated at the beam qualities Q and ^{60}Co, whereas those in $k'_{R_{50}}$ need to be evaluated at the beam qualities Q and Q_{ecal}. The choice of the value of Q_{ecal}, required for the calculation of k_{ecal} or $k'_{R_{50}}$, is completely arbitrary. A value of $R_{50} = 7.5$ g cm^{-2} has been chosen in the protocol. This choice minimizes the differences between cylindrical chambers of different r_{cav} because it is at high energy (Andreo et al. 2000).

According to TG-51 formalism, plane-parallel chambers must be used for reference dosimetry in electron beams of energies 6 MeV or less. At higher energies their use is recommended but not required.

Although the protocol allows for the use of plane-parallel chambers that have been calibrated in a ^{60}Co beam, it recommends that, when possible, plane-parallel chambers be calibrated against a calibrated cylindrical ionization chamber in a high-energy electron beam of quality Q_{cross}. The cross-calibration procedure consists of first measuring the beam quality R_{50} and reference depth d_{ref} at the beam quality Q_{cross}. Measurements are then made, in sequence, with the point of measurement of both the calibrated cylindrical chamber and the plane-parallel chamber at d_{ref}. The cross-calibration technique determines the product $\left[k_{ecal} N^{^{60}Co}_{D,w}\right]^{pp}$ for the plane-parallel chamber as

$$\left[k_{ecal}N_{D,w}^{^{60}Co}\right]^{pp}=\frac{\left(D_w^Q\right)^{cyl}}{\left(Mk'_{R_{50}}\right)^{pp}}=\frac{\left(MP_{gr}^{Q}k'_{R_{50}}\,k_{ecal}N_{D,w}^{^{60}Co}\right)^{cyl}}{\left(Mk'_{R_{50}}\right)^{pp}}.\qquad [\mathrm{Gy/C}] \tag{7.6}$$

This product is then used in

$$D_w^Q=MP_{gr}^{Q}k'_{R_{50}}\left[k_{ecal}N_{D,w}^{^{60}Co}\right]^{pp}\qquad [\mathrm{Gy}] \tag{7.7}$$

for the determination of absorbed dose to water at all electron beam energies using the cross-calibrated plane-parallel ionization chamber.

3. Implementation

3.1 Calibration of Ionization Chambers in a ^{60}Co Beam

When an ionization chamber or dosimeter is sent to a standards laboratory for calibration, stability check measurements (using a suitable check device) must be done by the user before and after the calibration. At least two independent checks should be performed prior to sending the chamber for calibration and the same checks repeated when the chamber is returned. This will ensure that the chamber response has not been affected during transport. With adequate checks in place, it is necessary to have the chamber calibrated when first purchased, when repaired, when the redundant check suggests a need, or once every 2 years.

The Accredited Dosimetry Calibration Laboratories (ADCLs) have established the absorbed dose to water, $D_w^{^{60}Co}$, at a known depth of 5 g cm^{-2} in a water phantom. This is realized by the ADCLs by means of a calibrated cavity ionization chamber, performing measurements in a water phantom. The user chamber is placed with its point of measurement at a depth of 5 g cm^{-2} in a water phantom and its calibration coefficient $N_{D,w}^{^{60}Co}$ is obtained from

$$N_{D,w}^{^{60}Co}=\frac{D_w^{^{60}Co}}{M},\qquad [\mathrm{Gy/C}] \tag{7.8}$$

where M is the reading of the dosimeter corrected for the influence quantities, in order to correspond to the reference condition for which the calibration coefficient is valid.

3.1.1 Reference Conditions

Reference conditions are conditions for which the calibration coefficients of various instruments are valid without any further correction factors. These include the phantom material and dimension, the depth of measurement, the field size, the source-to-surface distance (SSD), and the ambient temperature, pressure, and relative humidity. If measurements are made under the reference conditions that are identical to those used at the standards laboratory, then no correction to the chamber reading is necessary to determine D_w^Q. On the other hand, if measurement conditions are different from the reference conditions used at the standards laboratory, then the chamber reading should be corrected for any differences between the ambient air conditions affecting the chamber at the time of measurement and the standard ambient air conditions for which the calibration coefficient is applied. Corrections should also be made for ionic recombination and polarity effects. Furthermore, when measurements are made in a beam quality Q that is different from the reference beam quality ^{60}Co, then the differences in beam quality are accounted for by using a beam quality conversion factor k_Q.

3.1.2 Traceability

To ensure uniformity of dosimetry in external beam radiation therapy using high-energy photons and electrons, the absorbed dose to water calibration coefficient of an ionization chamber, $N_{D,w}^{^{60}Co}$, must be traceable to national standards of absorbed dose to water. The National Institute of Standards and Technology (NIST) in the United States and National Research Council of Canada (NRCC) maintain these standards. Traceability is also maintained if the calibration coefficient is obtained from an ADCL.

3.2 Ionization Chambers

Only cylindrical ionization chambers are allowed for reference dosimetry in high-energy photon beams. The protocol provides calculated values of k_Q for various cylindrical ionization chamber types as a function of photon beam quality $\%dd(10)_x$. Only when a plane-parallel ionization chamber has been calibrated in the same beam quality as the user beam can this chamber be used for measurements in reference conditions.

Both cylindrical and plane-parallel chambers are recommended for use in high-energy electron beams. For energies of 6 MeV and less, plane-parallel chambers must be used for reference dosimetry. The protocol provides calculated values of k_{ecal} for various cylindrical and plane-parallel ionization chamber types and values of $k'_{R_{50}}$ as a function of electron beam quality R_{50} for various cylindrical and plane-parallel chambers.

3.3 Phantoms

Clinical reference dosimetry must be performed in a water phantom. This is to ensure simplicity and accuracy in the protocol by minimizing the uncertainties due to the recognized problems associated with other phantom materials, i.e., the need to scale depth, fluence ratios, and charge storage problems in insulating materials and variability in density of different batches of plastic phantoms. The lateral dimensions of the phantom should be large so that adequate margin can be given to the largest field size employed at the depth of measurement to provide equilibrium of scatter into the central axis. A phantom with dimensions of at least $30 \times 30 \times 30$ cm^3 is adequate.

For horizontal beams, if the window of the phantom is greater than 2 mm thick, then all depths should be scaled to water-equivalent depths. For a window made of PMMA (polymethylmethacrylate), the water-equivalent thickness is calculated as the measured thickness in centimeters times the factor 1.12.

Reference dosimetry measurements in plastic phantoms, including water-equivalent plastic phantoms, are not allowed. Plastic phantoms may be used for routine quality assurance (QA) checks, provided the relationship between dosimeter readings in plastic and water has been established for the user beam at the time of calibration.

3.4 Waterproof Sleeve for the Chamber

Chambers that are inherently waterproof can be used directly in water, thus avoiding the complications of extra waterproofing. For non-waterproof chambers, the same waterproofing sleeve that was used for calibrations of the user's ionization chamber at the standards laboratory should also be used for clinical reference dosimetry. However, if use of the same waterproofing sleeve is not possible, then another sleeve of the same material and of similar thickness should be used. The recommended material for waterproofing sleeve is PMMA no thicker than 1 mm to minimize the perturbation effect and to allow the chamber to reach thermal equilibrium with the water rapidly. The air gap between the chamber wall and the waterproofing sleeve should be less than or equal to 0.2 mm to allow the pressure in the chamber to reach ambient air pressure quickly. Latex condoms can also be used to waterproof a chamber. However, manufacturers usually coat the inner surface of these condoms with fine talcum powder, which can find its way inside the chamber cavity and affect the chamber response. The user should therefore ensure that talcum powder is not used inside latex condoms.

3.5 Positioning of the Ionization Chamber at the Reference Depth

When measurements are made under reference conditions, the "point of measurement" should be positioned at the reference depth of measurement in the water phantom.

3.6 Correction for Influence Quantities

The calibration coefficient for an ionization chamber is valid only for the reference conditions that apply to the calibration. Any departure from the reference conditions when using the ionization chamber in the user beam should be corrected for using appropriate factors. These are described in the following paragraphs.

3.6.1 Temperature, Pressure, and Relative Humidity

Standards laboratories (or ADCLs) in the United States and in Canada provide calibration coefficients under standard environmental conditions of temperature T_0 = 22 °C, pressure P_0 = 101.33 kPa, and a relative humidity between 20% and 80%. If measurement conditions in the clinic are different from the standard conditions in the standards laboratories, then the response of a vented ionization chamber will change. The correction factor

$$P_{TP} = \frac{273.2 + T}{273.2 + 22.0} \frac{101.33}{P} \tag{7.9}$$

should be applied to convert the cavity air mass to the reference conditions. T is the temperature in degree Celsius in the water near the ion chamber and P is the pressure in kilopascals (not corrected to sea level and including temperature and latitude corrections for a mercury barometer).

Chambers require time to reach thermal equilibrium with their surroundings. Enough time should be allowed for the dosimeter to reach thermal equilibrium with its surroundings. When the temperature of the air inside the chamber is the same as the temperature of the water near the chamber, the changes in chamber output due to temperature variation is negligible. The temperature of the air in a chamber cavity should be taken to be that of the phantom, which should be measured; this is not necessarily the same as the temperature of the surrounding air.

3.6.2 Electrometer Calibration

Electrometers and ionization chambers can be calibrated separately. If the electrometer and the ionization chamber are calibrated as a unit, then the combined calibration coefficient will be given in units of Gy/rdg or Gy/C (depending on electrometer readout) and P_{elec} has a value of unity. P_{elec} also has a value of unity when cross-calibrations are performed in electron beams because it cancels out in the final equation. If the electrometer is calibrated separately from the ionization chamber, the electrometer correction factor, P_{elec}, is just the electrometer calibration coefficient which corrects the electrometer reading to true coulombs.

3.6.3 Polarity Effect

The reading of an ionization chamber may change when polarizing potentials of opposite polarity are applied to it. In photon beams, the polarity effect or its variation with beam quality is generally negligible. However, in electron beams the polarity effect can be significant, especially for plane-parallel chambers. The correction for polarity effect is given by:

$$P_{pol} = \left| \frac{\left(M_{raw}^{+} - M_{raw}^{-} \right)}{2M_{raw}} \right|, \tag{7.10}$$

where M_{raw}^{+} is the electrometer reading when positive charge is collected; M_{raw}^{-} is the reading when negative charge is collected; and M_{raw} is the reading obtained with the polarity used at the chamber calibration (positive or negative; i.e., M_{raw}^{+} or M_{raw}^{-}). The signs of M_{raw} ***must*** be used. Usually M_{raw}^{+} and M_{raw}^{-} have opposite signs unless the polarity independent background is large.

After reversing polarity, adequate time must be allowed before taking the next reading so that the ion chamber's reading can reach equilibrium. Depending on the chamber type and polarity, some chambers may take several minutes (up to 20 minutes) before stable operating condition is reached. Stable conditions can also be accomplished by irradiating the chamber to 3 to 5 Gy. If incorrectly accounted for, the polarity effect may result in errors, which are larger than the effects for which one is correcting.

For photon beams with energies less than or equal to 6 MV, if the polarity correction is different from unity by more than 0.3%, then the user should establish what the value of P_{pol} is in the calibrations laboratory's ^{60}Co beam. This can be established by contacting the calibration laboratory. If there is a significant polarity correction in the calibration laboratory's ^{60}Co beam, then the user should use $N_{D,w}^{^{60}Co} \big/ P_{pol}^{^{60}Co}$ instead of $N_{D,w}^{^{60}Co}$ when using the protocol.

3.6.4 Ion Recombination

In an ion chamber cavity some electrons and positive ions recombine before being collected. Therefore, a correction factor is required to correct for this lack of 100% charge collection. This correction factor has two components: an initial recombination and a general or volume recombination. The initial recombination is independent of dose rate and results from the recombination of ions formed by a single ionizing particle track. On the other hand, the general or volume recombination results from the recombination of ions formed by separate ionizing particle tracks. Its magnitude depends on the density of ionizing particles in the cavity and therefore on the dose rate. Both of these effects depend on the geometry of the chamber and on the applied collection voltage. In accelerator beams, the correction for ion recombination will thus change if either the pulse rate for a fixed dose rate or the dose rate is changed.

The initial recombination effect is small: about 0.1% for cylindrical chambers and collection voltages typically used in radiotherapy. For plane-parallel chambers the effect is about 0.1% to 0.2%. The same is also true for general combination for continuous radiation (^{60}Co beams). However, the effect of general recombination can be significant for pulsed beams and especially for pulsed scanned (swept) beams.

The protocol recommended the "two-voltage" method to measure P_{ion}. In this method the ionization is measured at two different collecting voltages under the same irradiation conditions. Let M_{raw}^{H} and M_{raw}^{L} denote the raw chamber readings when the collecting voltages are V_H and V_L, respectively. Let V_H be the normal operating voltage, which is higher than V_L. The ratio V_H/V_L should have a value of at least 2. Assuming a linear dependence of $1/M_{raw}$ on $1/V^2$, the correction factor P_{ion} for continuous (i.e., ^{60}Co) beams can be obtained from the following equation:

$$P_{ion}\left(V_H\right)=\frac{1.-\left(\frac{V_H}{V_L}\right)^2}{\frac{M_{raw}^H}{M_{raw}^L}-\left(\frac{V_H}{V_L}\right)^2}. \tag{7.11}$$

Equation (7.11) extracts an estimate of the general recombination. The presence of initial recombination disturbs the linearity of $1/M_{raw}$ on $1/V^2$. However, this is a small effect and can be neglected.

For pulsed or pulsed-swept beams one assumes a linear dependence of $1/M_{raw}$ on $1/V$ and uses the following expression for P_{ion}:

$$P_{ion}\left(V_H\right)=\frac{1.-\frac{V_H}{V_L}}{\frac{M_{raw}^H}{M_{raw}^L}-\frac{V_H}{V_L}}. \tag{7.12}$$

The value of P_{ion} must be measured for each chamber beam combination. If P_{ion} has a value greater than 1.05, then the uncertainty in P_{ion} becomes unacceptably large. In these situations, the protocol recommends that another chamber with a smaller value of P_{ion} be used.

4. Photon Beams

4.1 Determination of Absorbed Dose to Water

4.1.1 Reference Conditions

Clinical reference dosimetry is performed in an open beam. The point of measurement of the cylindrical chamber should be positioned at a water-equivalent reference depth of 10 cm in a water phantom. The reference conditions for the determination of absorbed dose in the user beam are given in table 7-1.

4.1.2 Determination of Absorbed Dose Under Reference Conditions

The absorbed dose to water at the reference depth in water, in a photon beam of quality Q and in the absence of the chamber, is given by equation (7.1), i.e.,

$$D_w^Q = Mk_Q N_{D,w}^{^{60}Co}. \tag{7.1}$$

Table 7-1. Reference Conditions for Absorbed Dose Determination in the User Photon Beam

SSD or SAD (cm)	Field size (cm × cm)	Depth (g cm^{-2})
100 or the normal clinical distance	10×10	10

SAD: Source-to-axis distance
SSD: Source-to-surface distance

The charge reading M should be corrected for the various influence quantities described in section 3. Equation (7.2) has been used for the calculation of k_Q for various cylindrical chamber types (see chapter 10). These values of k_Q are used with equation (7.1) for reference dosimetry in photon beams. The protocol provides tabulated as well as graphical values of k_Q as a function of beam quality for various cylindrical ionization chamber types.

4.2 Beam Quality Specification

The beam quality for photon beams is specified by $\%dd(10)_x$, the percentage depth dose at 10 cm depth in a water phantom due to photons only (i.e., excluding electron contamination effects). The subscript "x" in $\%dd(10)_x$ is important. It denotes PDD with electron contamination removed. The protocol provides values of k_Q as a function of $\%dd(10)_x$ for various cylindrical chamber types.

4.3 Measurement of Beam Quality Index

The first step in specifying $\%dd(10)_x$ is to measure the central axis percent depth-dose (PDD) curve for the beam in question. $\%dd(10)_x$ must be measured in a water phantom with an SSD of 100 cm and a field size of 10 cm × 10 cm at the phantom surface. When cylindrical chambers are used for measurements, the first step is to generate central axis percent depth-ionization (PDI) data by identifying the point of measurement as the assumed depth. This is shown by curve I in figure 7-1a. The next step is to shift the entire curve to shallower depths by a distance equal to 0.6 r_{cav}, where r_{cav} is the internal radius of the chamber cavity. This is shown by curve II in figure 7-1a. The value of percent depth-ionization at point A on curve II (i.e., at 10 cm depth) gives %dd(10). The shifted percent depth-ionization curve (curve II) can be treated as percent depth-dose curve because the variation in stopping-power ratio is less than 0.1% past $d_{\max}$ and hence can be neglected. The PDD curve thus generated also neglects any variation in P_{ion} and P_{pol} with depth. It is this PDD curve (i.e., curve II in figure 7-1a) that should be used for beam quality specification. If plane-parallel chambers are used for measurements, then it is not necessary to shift curve I in figure 7-1a. This is because the point of measurement and *the effective*

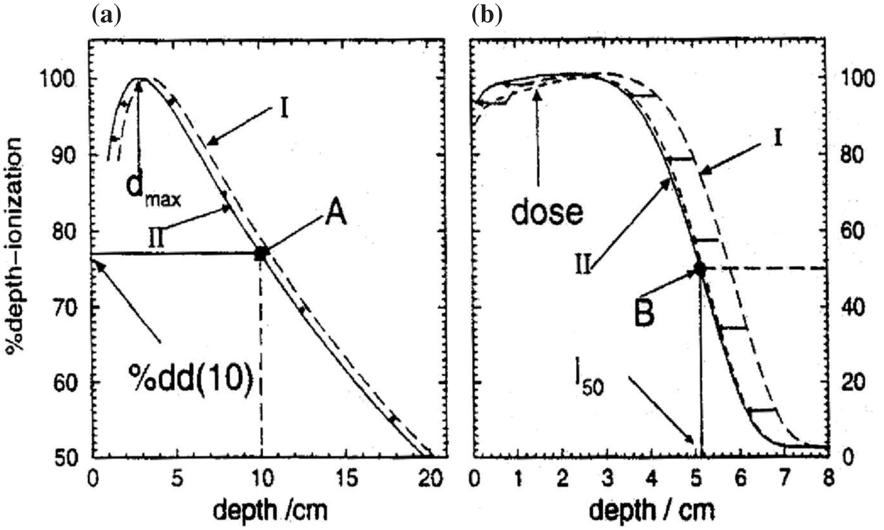

Figure 7-1. Effect of shifting depth-ionization data measured with cylindrical chambers upstream by 0.6 r_{cav} for photon beams (a) and by 0.5 r_{cav} for electron beams (b) [with r_{cav} = 1.0 cm]. The measured data are shown by dashed lines and the shifted data by solid lines in both panels. The value of percent depth-ionization at point A on curve II at 10 cm depth (a) gives the value of PDD at 10 cm depth for photon beams. In (b), the value of percent depth-ionization (PDI) at point B gives I_{50} from which R_{50} can be determined using equations (7.17) and (7.18). For photon beams, curve II in (a) can be considered as the PDD curve and for electron beams curve II in (b) will need to be corrected further by using water-to-air stopping-power ratios and ratios of various perturbation correction factors to obtain the percentage depth-dose curves (short dashed curves). (Reprinted from TG-51 protocol: Almond et al. (1999), Figure 1, with permission from AAPM.)

point of measurement of the plane-parallel chamber are the same and they are placed at the measurement depth. Curves I and II in figure 7-1a are then coincident. The unshifted percent depth-ionization curve is thus treated as a PDD curve for the purpose of beam quality specification.

If the energy of the photon beam is greater than or equal to 10 MV, then the protocol recommends that a 1 mm Pb (lead) foil should be placed at specified locations below the accelerator head in the path of the beam. The value of $\%dd(10)_x$ is then derived from the measured value of percent depth dose at 10 cm depth, $\%dd(10)_{Pb}$, with the lead in place. Below 10 MV, there is no need to place the lead foil in the path of the beam and one measures %dd(10) in an open beam. In these situations $\%dd(10)_x = \%dd(10)$. When the beam energy is greater than 10 MV, the value of $\%dd(10)_x$ for the open beam is obtained from the value of $\%dd(10)_{Pb}$ measured with the foil in the beam at 50±5 cm from the phantom surface by

$$\begin{aligned}\%dd(10)_x &= [0.8905 + 0.00150\ \%dd(10)_{Pb}]\ \%dd(10)_{Pb}\\ &\quad \text{for} \quad \%dd(10)_{Pb} \geq 73\%,\end{aligned} \tag{7.13}$$

and, if the foil is placed at 30±1 cm from the phantom surface, by

$$\begin{aligned}\%dd(10)_x &= [0.8116 + 0.00264\ \%dd(10)_{Pb}]\ \%dd(10)_{Pb}\\ &\quad \text{for} \quad \%dd(10)_{Pb} \geq 71\%.\end{aligned} \tag{7.14}$$

If $\%dd(10)_{Pb}$ is less than the respective thresholds given in equations (7.13) and (7.14), then $\%dd(10)_x = \%dd(10)_{Pb}$. In calculating $\%dd(10)_x$ from equations (7.13), and (7.14), one should use the values of $\%dd(10)_{Pb}$ and not the fractional depth dose.

The protocol recommends a general formula to correct for electron contamination as an interim measure for machines with 45 cm or more clearance between the jaws and the phantom surface. For beam energies below 10 MV with $\%dd(10) \leq 75\%$, $\%dd(10)_x = \%dd(10)$. For higher-energy beams the following equation applies up to $\%dd(10) = 89\%$:

$$\begin{aligned}\%dd(10)_x &= 1.267\ \%dd(10) - 20.0\\ &\quad [\text{for} \quad 75\% < \%dd(10) \leq 89\%],\end{aligned} \tag{7.15}$$

where %dd(10) is measured as described above for an open beam. This formula is based on a global fit and for a high-energy beam may cause errors in assigning $\%dd(10)_x$ of up to 2% in extreme cases. This would lead to an error in k_Q and hence absorbed dose of 0.4%.

4.4 Calibration Measurements

The lead foil should be removed when measurements are made under reference conditions for absolute calibration of photon beams.

4.5 Absorbed Dose to Water at d_{max}

Equation (7.1) determines the absorbed dose to water at 10 cm depth under reference conditions. The dose at the depth of dose maximum or at any other depth can be obtained by using the appropriate clinical PDD curve for SSD setups and clinical tissue-phantom ratio (TPR) or clinical tissue-maximum ratio (TMR) curves for source-to-axis distance (SAD) setups.

4.6 Summary of Do's and Don'ts

- For absolute calibration measurements, position the central axis of the cylindrical chamber at 10 cm depth in a water phantom.
- Correct the raw charge reading M_{raw} for the influence quantities described in section 3.
- The signs of M_{raw}, M^{+}_{raw}, and M^{-}_{raw} must be included into the equation of polarity effect.
- Measure P_{ion} for each chamber beam combination.
- All beam quality measurements must be made using an SSD of 100 cm and a field size of 10 cm × 10 cm at the water phantom surface. For beam energies greater than or equal to 10 MV, place a 1 mm Pb foil in the path of the beam at 50±5 cm or 30±1 cm from the water phantom surface. Use the appropriate equations for calculations of $\%dd(10)_x$.
- Use the values of $\%dd(10)_{Pb}$ in equations (7.13) and (7.14) for the calculation of $\%dd(10)_x$. Do not use fractional depth dose.
- Remove the Pb filter for *all* calibration measurements.
- If a cylindrical chamber is used for measurements of the central axis depth-dose curve, then shift the measured percent depth-ionization curve by 0.6 r_{cav}, where r_{cav} is the radius of the ionization chamber cavity. Use the shifted curve to determine PDD at 10 cm depth. It is this value of PDD that should be used for the determination of beam quality.
- If plane-parallel chambers are used for measurements of the central axis depth-dose curve, then no shift is necessary. Treat the unshifted curve as the PDD curve for the determination of PDD at 10 cm depth.

5. Electron Beams

5.1 Determination of Absorbed Dose to Water

5.1.1 Reference Conditions

The "point of measurement" of the cylindrical and plane-parallel chamber should be positioned at the reference depth, which is at a water-equivalent depth of

$$d_{ref} = 0.6\,R_{50} - 0.1\ \text{(cm)}. \tag{7.16}$$

The reference conditions for the determination of absorbed dose to water in the user electron beams are given in table 7-2.

Table 7-2. Reference Conditions for Absorbed Dose Determination in the User Electron Beam

SSD[†]	R_{50}(g cm^{-2})	Field size (cm × cm)	Depth (g cm^{-2})
90–110[†]	≤8.5	≥10×10	$d_{ref} = 0.6\,R_{50} - 0.1$
90–110[†]	>8.5	≥20×20	$d_{ref} = 0.6\,R_{50} - 0.1$

[†] Measurement of R_{50} must be done with SSD = 100 cm.

5.1.2 Determination of Absorbed Dose Under Reference Conditions

The absorbed dose to water at the reference depth d_{ref} in water, in an electron beam of quality Q, and in the absence of the chamber, is given by equation (7.5), i.e.,

$$D_w^Q = MP_{gr}^Q k'_{R_{50}} k_{ecal} N_{D,w}^{^{60}Co}. \qquad \text{[Gy]} \qquad (7.5)$$

As before, M should be corrected for the influence quantities described in section 3. The protocol provides values of $k'_{R_{50}}$ as a function R_{50} and tabulated values of k_{ecal} for various cylindrical and plane-parallel ionization chambers.

5.2 Beam Quality Specification

For electron beam reference dosimetry the beam quality is specified by the depth in water at which the absorbed dose falls to 50% of the maximum dose. This depth is denoted by R_{50}.

5.3 Measurement of Beam Quality Index

The first step in determining R_{50} is to measure central axis percent depth-ionization curve for the beam in question. This must be measured in a water phantom with an SSD of 100 cm and a field size ≥ 10 cm × 10 cm at the phantom surface (or ≥ 20 cm × 20 cm for $R_{50} > 8.5$ cm, i.e., E > 20 MeV). The procedure recommended in section 4.3 should be followed for the measurement of central axis percent depth-ionization curve. If cylindrical ionization chambers are used, then the depth-ionization curve should be generated first by identifying the point of measurement as the assumed depth (curve I in figure 7-1b). In the next step the entire depth-ionization curve should be shifted towards the shallower depth by 0.5 r_{cav}, where r_{cav} is the internal radius of the chamber cavity (curve II in figure 7-1b). If plane-parallel chambers are used, then no shift of the depth-ionization curve is necessary. In that case, curves I and II are coincident. The percent depth-ionization curve thus generated neglects any variation in P_{ion} and P_{pol} with depth and also ignores variations in the electron fluence correction factor. It is this percentage depth-ionization curve (i.e., curve II in figure 7-1b) that should be used for beam quality specification.

The next step is to locate point B at the level of 50% of the ionization maximum on curve II (figure 7-1b). The depth of point B gives I_{50}. The beam quality specifier, R_{50}, is then determined from measured values of I_{50} using the following two equations:

$$R_{50} = 1.029\, I_{50} - 0.06 \text{ (cm)} \qquad (\text{for} \quad 2 \le I_{50} \le 10 \text{ cm}), \tag{7.17}$$

or

$$R_{50} = 1.059\, I_{50} - 0.37 \text{ (cm)} \qquad (\text{for} \quad I_{50} > 10 \text{ cm}). \tag{7.18}$$

The protocol also suggests that a good quality diode detector, which responds as a dose detector in an electron beam, could be used for the determination of PDD curves. However, the protocol cautions that one must establish that this condition is fulfilled. An alternate method is to convert the percent depth-ionization curve for an ionization chamber to a PDD curve using the recommendations outlined in section 6.

5.4 Calibration Measurements

When measurements are made under reference conditions for absolute calibration of electron beams, the central axis of a cylindrical chamber or the inner surface of the front window of the plane-parallel chamber should be positioned at the reference depth d_{ref} in a water phantom. If a cylindrical chamber is used, then P_{gr}^{Q} should be accurately determined from the following equation:

$$P_{gr}^{Q} = \frac{M_{raw}\left(d_{ref} + 0.5\, r_{cav}\right)}{M_{raw}\left(d_{ref}\right)}, \tag{7.19}$$

where the symbols on the right hand side of equation (7.19) represent the ratio of integrated charges or ionization currents with the central axis of the chamber positioned at $d_{ref} + 0.5\, r_{cav}$ and d_{ref}. P_{gr}^{Q} is less than 1 for $d_{ref} > (d_{\max} + 0.5\, r_{cav})$. For plane-parallel chambers P_{gr}^{Q} has a value of unity. The value of D_{w}^{Q} is then determined from equation (7.5).

5.5 Absorbed Dose to Water at $d_{\max}$

Equation (7.5) determines the absorbed dose to water at the depth of d_{ref} under reference conditions. Dosimetry calculations in the clinic are usually performed by taking the depth of $d_{\max}$ as the reference depth. The dose at $d_{\max}$ for a given beam should be determined from the dose at d_{ref} by using the clinical PDD curve for that beam. The recommendations of the AAPM TG-25 report (Khan et al. 1991) should be followed for the determination of PDD curves. However, in order to be consistent with the TG-51 recommendations the expression presented by Burns et al.

(1996) for stopping-power ratios in realistic electron beams should be used (see chapter 13). The dose at $d_{\max}$ is then obtained by dividing the dose at d_{ref} with the fractional depth-dose at d_{ref}.

5.6 Summary of Do's and Don'ts

- For absolute calibration measurements, position the central axis of the cylindrical chamber at the reference depth d_{ref} in a water phantom. If plane-parallel ionization chambers are used, then position the inner surface of the front window at the reference depth d_{ref}.
- For beam energies of 6 MeV or less, use a plane-parallel ionization chamber for absolute dose measurements.
- Correct the raw charge reading M_{raw} for the influence quantities described in section 3.
- The signs of M_{raw}, M_{raw}^{+} , and M_{raw}^{-} must be included into the equation of polarity effect.
- Measure P_{ion} for each chamber beam combination.
- All beam quality measurements must be made using an SSD of 100 cm and a field size on the phantom surface $\geq$ 10 cm × 10 cm ($\geq$ 20 cm × 20 cm for $R_{50} > 8.5$ cm, i.e., E > 20 MeV).
- If a cylindrical chamber is used for measurements of the central axis depth-dose curve, then shift the measured percent depth-ionization curve by 0.5 r_{cav}, where r_{cav} is the radius of the ionization chamber cavity. Use the shifted curve to determine the depth of 50% of the maximum ionization, I_{50}. It is this value of I_{50} that should be used for the determination of R_{50} using equation (7.17) or (7.18).
- If plane-parallel chambers are used for measurements of the central axis depth-dose curve, then no shift is necessary. The unshifted curve should be used for the determination of I_{50}.
- To obtain the dose at $d_{\max}$ from that at d_{ref}, divide the dose at d_{ref} by the fractional depth-dose at d_{ref}. Use the clinical PDD curve to determine the fractional depth-dose at d_{ref}.
- Use the equation for Burns et al. (1996) (see chapter 13) for the calculation of water-to-air stopping-power ratios for realistic electron beams. Use these stopping-power ratio data to convert the percent depth-ionization (PDI) curve to a PDD curve.
- If well-guarded plane-parallel ionization chambers are used to measure PDD curves, then errors arising from perturbation correction factors are minimized.

6. Measurements of PDD Curves in Electron Beams

A detailed discussion on measurements of PDD curves in electron beams, including a discussion of errors, is given in chapter 12. The reader is directed to chapter 12 to gain an in-depth knowledge on how to measure PDD curves in electron beams.

7. What To Do with Ion Chambers Not Included in the TG-51 Protocol

- Find the closest matching chamber for which data are given.
- The critical features in order are: 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%.
- It is the responsibility of the user to confirm this by comparing the results to those of a calibrated cylindrical chamber for which data are given in the protocol.

8. Errors in the TG-51 Protocol

- *Figure 5:* PR06G curve appears twice on this curve. The correct curve is the lower curve, i.e., the curve that belongs to the group represented by NE2561, N2331, NE2581, PR06G.
- *Worksheet A:* Item 8a is missing two brackets and a squared symbol in the equation for P_{ion}, but equation (11) for P_{ion} is correct in the text of the protocol [equation (7.11) in this monograph].

References

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Problems

1. A PTW N30001 ion chamber and electrometer have been calibrated together at NRCC and $N_{D,w}^{^{60}Co}$ = 51.3 mGy/nC. The polarity correction is negligible in ^{60}Co beams. Measurements were made in an electron beam. The measured value of I_{50} is 8.2 cm. The measured ionization at the reference depth at 24 °C, 103 kPa, is 22.0 nC/MU in a 20×20 cm^2 field at SSD = 100 cm and for the standard operating voltage of 300 V. Under the same conditions, the reading after equilibrium is reached with an applied voltage of 150 V is 21.8 nC/MU, and after the voltage is switched to –300V is –22.1 nC/MU. For the beam in question the following values were measured in a 20×20 cm^2 field at SSD 100 cm, for the ionization per fixed number of monitor units:

   $$I(\text{reference depth} -1.5\text{ mm}) = 63.0\text{ nC}, I(\text{reference depth}) = 62.0\text{ nC},$$
   $$\text{and } I(\text{reference depth} +1.5\text{ mm}) = 61.2\text{ nC},$$

   where the depths correspond to the central axis of the ion chamber.
   a. What is the TG-51 beam quality specifier of the beam and its value?
   b. What is the reference depth (in cm)?
   c. What is the recombination correction?
   d. What is the polarity correction?
   e. What is D_w/MU, the dose to water per monitor unit, in the beam at the reference depth?

2. Your NE2561 ion chamber and electrometer have been calibrated together and $N_{D,w}^{^{60}Co}$ = 95.0 mGy/nC at standard temperature of 22 °C and 101.3 kPa. The recombination and polarity corrected ionization at 25 °C, 102 kPa, is 22 nC/MU at the reference depth in a 10×10 cm^2 field at SSD = 100 cm. For the beam in question the following values were measured in a 10×10 cm^2 field at SSD 100 cm, for the ionization per fixed number of monitor units:

   $$I_{\max} = 100\text{ nC}, I(10\text{ cm}) = 65\text{ nC}, I(10.2\text{ cm}) = 64.3\text{nC}, I(9.8\text{ cm}) = 65.6\text{ nC},$$

   where the depths correspond to the central axis of the ion chamber.
   a. What is the TG-51 beam quality specifier of the beam and its value?
   b. What is the temperature and pressure corrected reading at the reference depth?
   c. What is the reference depth in a photon beam?
   d. What is D_w/MU in the beam at (i) the reference depth and (ii) the depth of dose maximum?

3. When an NE2571 chamber is used for the calibration of electron beams, the TG-51 protocol recommends that the gradient correction P_{gr}^{Q} is measured as the ratio of integrated charges or ionization currents with the central axis of the chamber positioned at $d_{ref} + 0.5\ r_{cav}$ and d_{ref}. However, when the same chamber is used for photon beam calibrations, no explicit measurements are necessary for P_{gr}^{Q}. This is because, for photon beams.
   a. The effective point of measurement of the chamber is placed at the reference depth which accounts for the effects of P_{gr}^{Q}.
   b. The corrections for the gradient effect is included in the calculated values of k_Q.
   c. Gradient corrections are not necessary for photon beams when the "point of measurement" of the chamber is placed at the reference depth.
   d. Gradient correction is negligible in photon beams.

4. According to TG-51, the beam quality for an 18 MV photon beam should be measured by placing a lead filter in the path of the beam. This is because
   a. The lead filter stops all contaminant electrons from the accelerator head and does not act as additional source of electrons.
   b. The contaminant electrons from the accelerator head may affect the measured values of percentage depth dose at $d_{\max}$ only and hence does not affect $\%dd(10)_x$.
   c. Contaminant electrons affect the calculated values of k_Q.
   d. Contaminant electrons have no effect on the calculated values of k_Q.

5. The values of $k'_{R_{50}}$ at d_{ref} for a Markus chamber is different from those of a well-guarded plane-parallel ionization chamber at all beam qualities except at R_{50} = 7.5 cm. This is because
   a. At all beam qualities the wall correction factors for a Markus chamber are different from those of well-guarded plane-parallel chambers.
   b. The well-guarded plane-parallel chambers are constructed such that the electron fluence corrections are negligible at all beam qualities.
   c. The Markus chamber is constructed such that the electron fluence corrections are negligible at all beam qualities.
   d. The electron fluence corrections for a Markus chamber are different from those of well-guarded plane-parallel chambers.
   e. The only factors that contribute to the observed differences in $k'_{R_{50}}$ at d_{ref} are the water-to-air stopping-power ratios at beam qualities Q and Q_{ecal}.