Everything you wanted to know about the Practical Implementation of TG-51 protocol in the clinic

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Abstract

Task Group 51 (TG-51) of the Radiation Therapy Committee of the AAPM has published a new protocol for the calibration of high-energy photon and electron beams used in radiation therapy. 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. This is different from the recommendations given in the AAPM TG-21 protocol which are based on an exposure calibration factor of an ionization chamber in a ^{60}Co beam. The goal of this refresher course is to discuss the practical steps that are necessary to successfully implement the recommendations of the TG-51 protocol in the clinic. Information will be provided on the following topics: 1) Measuring percent depth-ionization and depth dose curves for photon and electron beams using cylindrical and plane-parallel ionization chambers. 2) Determining the beam quality conversion factor k_Q for photon beams and the electron beam quality conversion factor k'_{R50} for electron beams. 3) Measuring gradient correction factor P_{gr}^{Q} for cylindrical chambers in electron beams. 4) Measuring various correction factors to the charge reading. 5) Using cylindrical and plane-parallel ionization chambers for absolute calibration measurements. 6) Determining dose at the depth of dose maximum from measurements made at the reference depth for both photon and electron beams. 7) Taking measurements needed to compare the recommendations of the TG-51 protocol with those of the TG-21 protocol. 8) Identifying expected differences in absorbed doses between TG-51 and TG-21 for both photon and electron beams. 9) Identify the sources that contribute to the observed differences between the two protocols. 10) Clarify potential sources of confusion in the clinical implementation of TG-51.

1. Introduction

Task Group 51 of the Radiation Therapy Committee of the AAPM has published a new external beam dosimetry protocol (TG-51) that is based on the use of an ionization chamber calibrated in terms of absorbed dose-to-water in a standards laboratory's ^{60}Co gamma ray beam.[1] The recommendations of this protocol differ significantly from those given in the AAPM TG-21 protocol,[2] which is based on the exposure calibration factor of an ionization chamber in ^{60}Co gamma ray beam and a N_{gas} formalism for the determination of absorbed dose-to-water in reference conditions. The goal of this refresher course is to discuss the practical steps that are necessary to successfully implement the recommendations of the TG-51 protocol in the clinic.

At the conclusion of this refresher course, the attendee should be able to

1. Apply TG-51 protocol to calibrate photon and electron beams.
2. Use cylindrical and plane-parallel ionization chambers for the determination of percent depth ionization curves, percent depth dose curves and absorbed dose calibration for photon and beams in a water phantom.
3. Describe experimental techniques that will enable comparison of absorbed doses-to-water between TG-51 and TG-21 protocols.
4. Determine sources that contribute to the observed differences in absorbed dose between the TG-51 and TG-21 protocols, and identify the magnitude of the difference for each source.
5. Clarify various points of confusion that may arise when implementing the 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

$$D_w^Q = Mk_Q N_{D,w}^{60Co} \tag{1}$$

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. $N_{D,w}^{60Co}$ is the absorbed dose-to-water calibration factor of the user ionization chamber in a reference quality ^{60}Co beam.

The beam quality conversion factor k_Q is given by

$$k_Q = \frac{\left[\left(\overline{L}/r\right)_{air}^{w} P_{gr} P_{fl} P_{wall} P_{cel}\right]_Q}{\left[\left(\overline{L}/r\right)_{air}^{w} P_{gr} P_{fl} P_{wall} P_{cel}\right]_{60Co}} \tag{2}$$

where $P_{repl} = P_{gr}\, P_{fl}$. $\left(\overline{L}/r\right)_{air}^{w}$ is the water-to-air stopping power ratio; 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 which 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 lack of air equivalence of the

central electrode.

For electron beams, k_Q is written as a product of three factors, i.e., $k_Q = P_{gr}^Q k'_{R50} k_{ecal}$, 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 factor at ^{60}Co, $N_{D,w}^{60Co}$, into $N_{D,w}^{Qecal}$, where $N_{D,w}^{Qecal}$ is the absorbed dose-to-water calibration factor in an arbitrary electron beam of quality Q_{ecal}. k_{ecal} is given by:

$$k_{ecal} = \frac{\left[\left(\bar{L}/r\right)_{air}^{w} P_{fl} P_{wall} P_{cel}\right]_{Qecal}}{\left[\left(\bar{L}/r\right)_{air}^{w} P_{gr} P_{fl} P_{wall} P_{cel}\right]_{60Co}} \qquad (3)$$

The electron quality conversion factor k'_{R50} is needed to convert $N_{D,w}^{Qecal}$ into $N_{D,w}^{Q}$ for any beam of quality Q. k'_{R50} is given by

$$k'_{R50} = \frac{\left[\left(\bar{L}/r\right)_{air}^{w} P_{fl} P_{wall} P_{cel}\right]_{Q}}{\left[\left(\bar{L}/r\right)_{air}^{w} P_{fl} P_{wall} P_{cel}\right]_{Qecal}} \qquad (4)$$

Thus, for an electron beam, eq. (1) becomes

$$D_w^Q = M P_{gr}^Q k'_{R50} k_{ecal} N_{D,w}^{60Co} \qquad (5)$$

One of the advantages of expressing k_Q as a product of three terms is that the chamber to chamber variations of k'_{R50} is the same for all well guarded plane-parallel chambers. For cylindrical chambers, the variation in k'_{R50} is much smaller than the corresponding variation that would be obtained if Eq. (2) was used for the calculation k_Q. Note that the factors in Eq. (2) need to be evaluated at the beam qualities Q and ^{60}Co, whereas those in k'_{R50} 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'_{R50}, 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}.

According to TG-51, 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.

Cross calibration of a plane-parallel chamber against a reference (calibrated) chamber in a high-energy electron beam of quality Q_{cross} is recommended as the preferred method. The cross-calibration technique determines the product $[k_{ecal}N_{D,w}^{60Co}]^{pp}$ for the plane-parallel chamber. This product is then used in

$$D_w^Q = MP_{gr}^Q k'_{R50}\left[k_{ecal}N_{D,w}^{60Co}\right]^{pp} \quad (6)$$

for the determination o 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 repeat the same checks when the chamber is returned. This will ensure that the chamber response has not been affected by the transportation.
- 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 two years.
- The ADCLs have established the absorbed dose-to-water, D_w^{60Co}, 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 factor $N_{D,w}^{60Co}$ is obtained from

$$N_{D,w}^{60Co} = \frac{D_w^{60Co}}{M} \quad (7)$$

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 factor is valid.

3.1.1.Reference conditions

- Reference conditions are conditions for which the calibration factors 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, 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 factor 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 is 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 factor of an ionization chamber, $N_{D,w}^{60Co}$, must be traceable to national standards of absorbed dose to water. NIST in the USA and NRCC in Canada maintain these standards. Traceability is also maintained if the calibration factor is obtained form an Accredited Dosimetry Calibration Laboratory (ADCL).

3.2.Ionization chambers

- **Only cylindrical ionization chambers are allowed for reference dosimetry in high-energy photon beams**. The protocol provided calculated values of k_Q for various cylindrical chamber types as a function of beam quality %dd(10)$_x$. Only when a plane-parallel 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 provided calculated values of k_{ecal} for various cylindrical and plane-parallel ionization chamber types and values of k'_{R50} as a function of electron beam quality R_{50} for various cylindrical and plane-parallel chambers.

- 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.

- A detailed description about ionization chamber characteristics can be found in the IAEA TRS-398 Code of Practice.[3]

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 30x30x30 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, the water equivalent thickness is calculated as the measured thickness in cm 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 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 available, then another sleeve of the same material and of similar thickness should be used. The recommended material for waterproofing sleeve is polymethylmethacrylate (PMMA) no thicker than 1 mm 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.

- Plane-parallel chambers, if not waterproof, should also be enclosed in a waterproof enclosure. The waterproofing enclosure should preferably be made of the major material of the chamber no more than 1 mm thick.

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. Practical considerations for measurements in the user beam

- Check the integrity of waterproofing sleeve.
- Verify the stability of the dosimeter system using a check source.
- Allow enough time for the dosimeter to reach thermal equilibrium with its surroundings.
- Pre-irradiate the ionization chamber with 2-5 Gy to achieve charge equilibrium in the different materials.

- When polarity or polarizing voltages are modified allow enough time so that the ion chamber's reading can reach equilibrium.
- Measure leakage current before and after irradiation. Its magnitude should be less than approximately 0.1% of the measurement current and normally of the same sign.
- For relative measurements, use an external monitoring dosimetry system to account for fluctuations in the radiation output.

3.7.Correction for influence quantities

The calibration factor for an ionization chamber is valid only for the reference conditions, which 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:

3.7.1.Temperature, pressure and humidity

- Standards laboratories (or ADCLs) in the US and in Canada provide calibration factors

  under standard environmental conditions of temperature $T_0 = 22^oC$, pressure $P_0 = 101.33$ kPa and a relative humidity between 20% and 80%. If measurement conditions in the clinic are different form the standard conditions in the standards laboratories then the response of a vented ionization chamber will change. The correction factor

$$P_{TP} = \frac{273.2 + T}{273.2 + 22.0} \frac{101.33}{P} \tag{8}$$

  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 latitude corrections for a mercury barometer).

- Allow enough time for the chamber to reach thermal equilibrium with its surroundings. 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.

3.7.2.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 factor 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.

3.7.3.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 the following expression:

$$P_{pol} = \left| \frac{\left(M^{+}_{raw} - M^{-}_{raw}\right)}{2M_{raw}} \right| \qquad (9)$$

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 (up to 20 minutes) before stable operating condition is reached. Stable conditions can also be accomplished by irradiating the chamber to 3-5 Gy. If incorrectly accounted for, the polarity effect may result in errors, which is larger than the effects for which one is correcting.

3.7.4.Ion recombination

- In an ion chamber cavity some electrons and positive ions recombine before being completely 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.

- 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 0.1-0.2%. The same is also true for general combination for continuous radiation (gamma ray beams). However, the effect of general recombination can be significant for pulsed beams and especially for pulsed scanned (swept) beams.

- The "two-voltage" method is used to measure P_{ion}. In this method the ionization is measured at two different collecting voltages under the same irradiation conditions. Let M^{H}_{raw} and M^{L}_{raw} 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 form the following equation:

$$P_{ion}(V_H) = \frac{1. - \left(\frac{V_H}{V_L}\right)^2}{\frac{M^H_{raw}}{M^L_{raw}} - \left(\frac{V_H}{V_L}\right)^2} \tag{10}$$

Eq. (10) 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}:

$$P_{ion}(V_H) = \frac{1. - \frac{V_H}{V_L}}{\frac{M^H_{raw}}{M^L_{raw}} - \frac{V_H}{V_L}} \tag{11}$$

If P_{ion} has a value greater than 1.05, then the uncertainty in P_{ion} becomes unacceptably large and another chamber with a smaller value of P_{ion} should be used.

- P_{ion} **must be measured for each chamber beam combination. Correct the readings for each voltage for polarity effect.**

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 I.

Table I: Reference conditions for absorbed dose determination in the user beam.

SSD or SAD (cm)	Field size (cm x cm)	Depth (g cm^{-2})
100 or the normal clinical distance	10x10	10 [d]

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 eq. (1), i.e.,

$$D_w^Q = Mk_Q N_{D,w}^{60Co} \quad (1)$$

The charge reading M should be corrected for the various influence quantities described in Section 3. Equation (2) has been used for the calculation of k_Q for various cylindrical chamber types. These values of k_Q are used with Eq. (1) for reference dosimetry in photon beams.

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 provided 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 central axis percent depth dose curve for the beam in question.

- %dd(10)$_x$ **must** be measured in a water phantom with a source-to-surface distance of 100 cm and a field size of 10 cm x 10 cm at the phantom surface.

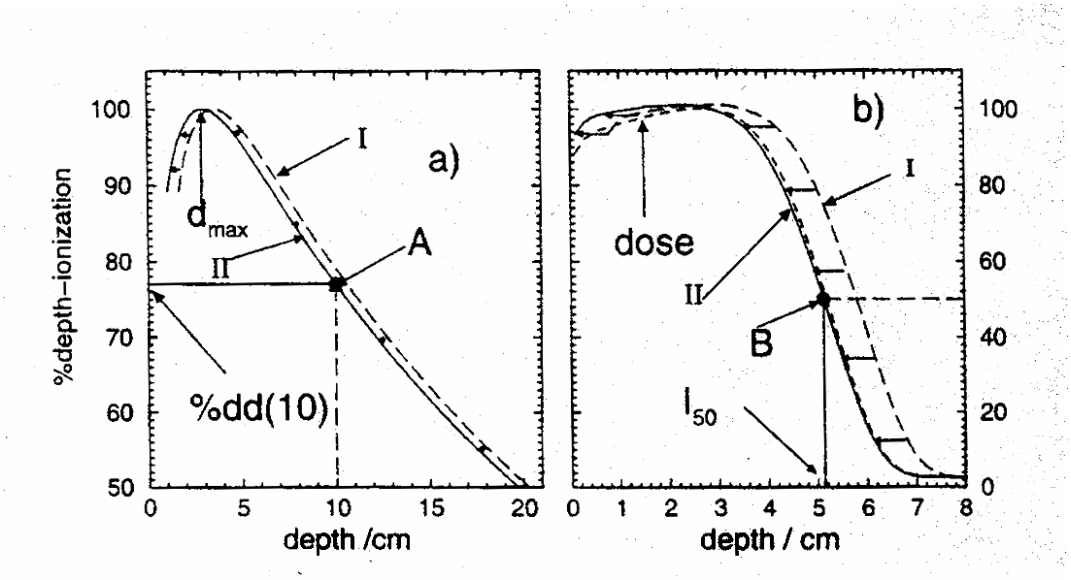

Fig. 1a

- When cylindrical chambers are used for measurements, the first step is to generate central axis percent depth-ionization data by identifying the *point of measurement* as the assumed depth. This is shown by curve I in Figure 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 chamber cavity. This is shown by curve II in Fig.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 percent depth dose curve thus generated also neglects any variation in P_{ion} and P_{pol} with depth. It is this percentage depth dose curve (i.e., curve II in Fig.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 Fig.1a. This is because the *point of measurement* and *the effective point of measurement* of the plane-parallel chamber are the same and they are placed at the measurement depth. Curves I and II in Fig.1a are then coincident. The unshifted percent depth ionization curve is thus treated as percent depth dose curve for the purpose of beam quality specification.
- For beam energies **greater than or equal to 10 MV a 1 mm Pb 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 Pb 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 $\%dd(10)_x = \%dd(10)$.

- The beam quality, $\%dd(10)_x$, is then determined as follows:
- For beams with energies less than 10 MV: $\%dd(10)_x = \%dd(10)$.
- For beams with energies greater than or equal to10 MV:
  Lead foil at 50±5 cm:

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

$$\text{for}\quad \%dd(10)_{pb} \geq 73\% \qquad (12)$$

Lead foil at 30±1 cm:

$$\%dd(10)_x = [0.8116 + 0.00264\ \%dd(10)_{pb}]\ \%dd(10)_{pb}$$

$$\text{for}\quad \%dd(10)_{pb} \geq 71\% \qquad (13)$$

If $\%dd(10)_{pb}$ is less than the respective thresholds given in equations (10) and (11), then

$\%dd(10)_x = \%dd(10)_{pb}$.

- In calculating $\%dd(10)_x$ from Eqs. (10), and (11) of the protocol, one should use the values of $\%dd(10)_{Pb}$ and **not the fractional** depth dose.

4.4. Calibration measurements

- The **lead foil should be removed when measurements are made for absolute calibration** of photon beams.

4.5.Absorbed dose at d_{max}

- Equation (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 percentage depth dose curve for SSD setups and clinical tissue-phantom ratio (TPR) or clinical tissue-maximum ratio (TMR) curves for SAD setups.

4.6Summary of Do's and Don'ts

- For absolute calibration measurements, position CAX 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 a SSD of 100 cm and a field size of 10 cm x 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 the equation (13) and (14) of the protocol 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 CAX 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 percent depth dose 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 CAX depth dose curve, then no shift is necessary. Treat the unshifted curve as 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** given by d_{ref} **= 0.6** R_{50} **- 0.1 (cm)**.

The reference conditions for the determination of absorbed dose to water in the user electron beams are given in Table II.

Table II: Reference conditions for absorbed dose determination in the user electron beam

SSD	R_{50} (g cm^{-2})	Field size (cm x cm)	Depth (g cm^{-2})
100	≤ 8.5	≥ 10 x 10	$d_{ref} = 0.6\ R_{50} - 0.1$
100	> 8.5	≥ 20 x 20	$d_{ref} = 0.6\ R_{50} - 0.1$

- Clinical reference dosimetry may be performed with an SSD from 90 to 110 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 eq. (3), i.e.,

$$D_w^Q = MP_{gr}^Q k'_{R50} k_{ecal} N_{D,w}^{60Co} \quad (3)$$

  As before, **M should be corrected for the influence quantities described in Section 3**.

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}.

- The protocol provided values of k'_{R50} as a function R_{50} for various cylindrical and plane-parallel ionization chambers.

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 a source-to-surface distance of 100 cm and a field size ^{3} 10 cm x 10 cm at the phantom surface.**

- 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 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 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 Fig.1b) that should be used for beam quality specification.

5.4. Calibration measurements

- Position the CAX of a cylindrical chamber or the inner surface of the front window of the plane-parallel chamber at the reference depth d_{ref} for calibration measurements.

- If a cylindrical chamber is used then measure P_{gr}^Q accurately following the guidelines given in the protocol. For pp chambers P_{gr}^Q has a value of unity.

5.5. Absorbed dose at d_{max}

- 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 percentage depth dose curve for that beam. The recommendations of the AAPM TG-25 report should be followed for the determination of percent depth dose curves. However, in order to be consistent with the TG-51 recommendations the expression presented by Burns et al for stopping power ratios in realistic electron beams should be used.

- Divide the dose at d_{ref} with the fractional depth dose at d_{ref} to get the dose at d_{max}.

5.6. Summary of Do's and Don'ts

- For absolute calibration measurements, Position CAX 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 beam calibration.

- 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 a SSD of 100 cm and a field size on the phantom surface = 10 cm x 10 cm (= 20x20 cm^2 for R_{50} > 8.5 cm i.e. E > 20 MeV).**

- If a cylindrical chamber is used for measurements of CAX 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 (16) or (17) of the protocol.

- If plane-parallel chambers are used for measurements of CAX 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 percent depth dose curve to determine the fractional depth dose at d_{ref}.

- Use the eq. for Burns et al[4] (eq. 14 below) for the calculation of water-to-air stopping power ratios for realistic electron beams. Use these stopping power ratio data to convert PDI curve to PDD curve.

- Use a well-guarded plane-parallel ionization chamber to measure percent depth-dose curves.

6.0. Measurements of PDD curves in electron beams

- Measure percent depth-ionization (PDI) distribution with a well-guarded plane-parallel ionization chamber. The water equivalent thickness (in $g.cm^{-2}$) of the front window and any waterproofing material should be taken into account when positioning the chamber at the position of interest. Determine the depth of the 50% of the maximum ionization on the depth-ionization curve. This depth gives I_{50}. Determine R_{50} using eq. (16) or (17) of the protocol as appropriate.

- Use the following equation:

$$\left(\frac{\overline{L}}{r}\right)_{air}^{w}(z, R_{50}) = \frac{a + b(\ln R_{50}) + c(\ln R_{50})^2 + d(z/R_{50})}{1 + e(\ln R_{50}) + f(\ln R_{50})^2 + g(\ln R_{50})^3 + h(z/R_{50})} \qquad (14)$$

where z denotes the depth of measurement and

a = 1.0752 b = -0.50867 c = 0.088670 d = -0.08402

e = -0.42806 f = 0.064627 g = 0.003085 h = -0.12460

to determine the values of water-to-air stopping-power ratio $\left(\overline{L}/r\right)_{air}^{w}$ at each depth. Multiply the PDI (z) by $\left(\overline{L}/r\right)_{air}^{w}$ and determine percent depth dose PDD(z). Renormalize to get the true PDD.

- From the PDD curve determine the depth of dmax, R_{50}, R_p (for TG-21). Be very careful with the software of the computerized scanner. Check the values by hand. It is convenient to look for 99.99% instead of 100%.
- Determine d_{ref} from eq. (18) of the protocol.

7.0. Comparison with TG-21 protocol

7.1. Photon beams

- All measurements should be made in a water phantom.
- Dose comparison should be done at the same depth. If measurements are done at 5 or 7 cm depth following TG-21 and at 10 cm depth following TG-51, then the data at 5 or 7 cm depth can be converted to those at 10 cm depth by using the clinical PDD curve or clinical TPR curves, as appropriate.
- Published data[5-7] indicate the doses determined by TG-51 are higher than those determine by TG-21 at all photon energies; at ^{60}Co, the ratio $D_w(TG-51)/D_w(TG-21)$ ranges from 1.1% to 2.2%; at 6 MV it ranges from 0.8% to 1.1% and at 18 MV it lies between

0.2 to 1.5%.

- Approximately 0.5% of the observed differences arise from the differences in the data used in the two protocols; about 0.15% difference arises from differences in beam quality specification; the largest difference of about 1.2 to 1.5% results from the influence of calibration factors based on different standards ($N_{D,w}^{60Co}$ vs. N_x).

7.2. Electron beams

- All measurements should be made in a water phantom.
- Dose comparison should be done at the same depth. The TG-51 recommended reference depth is given by $d_{ref} = 0.6R_{50} - 0.1$ (cm). TG-21 recommends that electron beams be calibrated at the depth of ionization maximum (**note: this is not the depth of dose maximum**). To compare $D_w^Q(d_{\max})_{TG-51}$ with $D_w^Q(d_{\max})_{TG-21}$ at the same depth of **dose maximum**, one needs to divide $D_w^Q(d_{ref})_{TG-51}$ with PDD (d_{ref}) and $D_w^Q(I_{\max})_{TG-21}$ with PDD (I_{max}). For this step, one needs to determine with care PDD (d_{ref}) and PDI (d_{ref}) from the percent depth dose curves generated in Section 6 above.
- The percent-depth ionization curves generated by a well-guarded plane-parallel ionization chamber should match within experimental uncertainties the 0.5 r_{cyl} shifted percent depth-ionization curves generated by a cylindrical ionization chamber.
- For TG-21 measurements the gradient correction P_{gr} (I_{max}) can be significant (approx. 1%) at low energies (i.e. 6 MeV) when calibration measurements are made using a cylindrical ionization chamber in conjunction with a depth-ionization curve measured by using a plane-parallel ionization chamber. This is inconsistent with the recommendations of TG-21 which states that P_{gr} (I_{max}) is unity at the calibration depth of ionization maximum.
- For TG-21, the mean energy $\overline{E}_0$ should be calculated from $\overline{E}_0 = 2.33 \times I_{50}$, where I_{50} is the depth of 50% ionization.
- For cross-calibration measurements, the *point of measurement* of all chambers should be placed at the depth of ionization maximum for TG-21 dosimetry and at the depth of d_{ref} for TG-51 dosimetry.
- Published data[5-8] indicate the doses determined by TG-51 are higher than those determined by TG-21 at all electron beam energies used in the clinic. For beam energies ranging from 6 to 20 MeV, the ratio $D_w(TG-51)/D_w(TG-21)$ ranges from about 1% to 3% when cylindrical chambers are used; for plane-parallel chambers this ratio ranges from about 1% to 2% for direct calibration procedure and 1% to 3% for cross-calibration procedure.
- The major factors that contribute to the observed differences between the two protocols

  are: i) the differences between the monoenergetic and realistic water-to-air stopping power ratios used in the two protocols; ii) differences in the values of P_{wall} at ^{60}Co; iii) the central electrode correction factor; iv) the differences between the measured and

calculated values of absorbed dose-to-water calibration factor, $N_{D,w}^{60Co}$, of the ionization chambers. This is related to the use of calibration factors based on different standards (i.e., $N_{D,w}^{60Co}$ vs. N_x); v) the differences in the measured values of the absorbed dose –to-water calibration factors, $N_{D,w}^{cross}$, obtained from cross-calibration of plane-parallel ionization chambers.

- The data and procedures recommended in TG-51 contribute a maximum difference of 1% in the determination of absorbed dose to water between the two protocols. Another 1% to 1.5% difference between the two protocols occurs due to the change of standards of air-kerma to standards of absorbed dose-to-water in ^{60}Co beams.

8.0 What to do with chambers not included in the protocol?

- Find the closest matching chamber for which data is 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%.
- 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.

9.0 ERRORS

- **Fig. 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 2 brackets and a squared symbol in the equation for P_{ion} but eq. 11 for P_{ion} is correct in the text.

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