# AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams

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(Received 17 September 1998; accepted for publication 4 June 1999)

A protocol is prescribed for clinical reference dosimetry of external beam radiation therapy using photon beams with nominal energies between $^{60}$Co and 50 MV and electron beams with nominal energies between 4 and 50 MeV. The protocol was written by Task Group 51 (TG-51) of the Radiation Therapy Committee of the American Association of Physicists in Medicine (AAPM) and has been formally approved by the AAPM for clinical use. The protocol uses ion chambers with absorbed-dose-to-water calibration factors, $N_{D,w}^{^{60}\mathrm{Co}}$, which are traceable to national primary standards, and the equation $D_w^Q = M k_Q N_{D,w}^{^{60}\mathrm{Co}}$, where $Q$ is the beam quality of the clinical beam, $D_w^Q$ is the absorbed dose to water at the point of measurement of the ion chamber placed under reference conditions, $M$ is the fully corrected ion chamber reading, and $k_Q$ is the quality conversion factor which converts the calibration factor for a $^{60}$Co beam to that for a beam of quality $Q$. Values of $k_Q$ are presented as a function of $Q$ for many ion chambers. The value of $M$ is given by $M = P_{\mathrm{ion}} P_{\mathrm{TP}} P_{\mathrm{elec}} P_{\mathrm{pol}} M_{\mathrm{raw}}$, where $M_{\mathrm{raw}}$ is the raw, uncorrected ion chamber reading and $P_{\mathrm{ion}}$ corrects for ion recombination, $P_{\mathrm{TP}}$ for temperature and pressure variations, $P_{\mathrm{elec}}$ for inaccuracy of the electrometer if calibrated separately, and $P_{\mathrm{pol}}$ for chamber polarity effects. Beam quality, $Q$, is specified (i) for photon beams, by $\%dd(10)_x$, the photon component of the percentage depth dose at 10 cm depth for a field size of $10\times10$ cm$^2$ on the surface of a phantom at an SSD of 100 cm and (ii) for electron beams, by $R_{50}$, the depth at which the absorbed-dose falls to 50% of the maximum dose in a beam with field size $\geqslant 10\times10$ cm$^2$ on the surface of the phantom ($\geqslant 20\times20$ cm$^2$ for $R_{50} > 8.5$ cm) at an SSD of 100 cm. $R_{50}$ is determined directly from the measured value of $I_{50}$, the depth at which the ionization falls to 50% of its maximum value. All clinical reference dosimetry is performed in a water phantom. The reference depth for calibration purposes is 10 cm for photon beams and $0.6R_{50} - 0.1$ cm for electron beams. For photon beams clinical reference dosimetry is performed in either an SSD or SAD setup with a $10\times10$ cm$^2$ field size defined on the phantom surface for an SSD setup or at the depth of the detector for an SAD setup. For electron beams clinical reference dosimetry is performed with a field size of $\geqslant 10\times10$ cm$^2$ ($\geqslant 20\times20$ cm$^2$ for $R_{50} > 8.5$ cm) at an SSD between 90 and 110 cm. This protocol represents a major simplification compared to the AAPM's TG-21 protocol in the sense that large tables of stopping-power ratios and mass-energy absorption coefficients are not needed and the user does not need to calculate any theoretical dosimetry factors. Worksheets for various situations are presented along with a list of equipment required. 
[S0094-2405(99)00209-6]

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## I. PREFACE

Advances in radiation dosimetry continue to improve the accuracy of calibrating photon and electron beams for radiation therapy. This document represents the third in a series of protocols adopted by the AAPM and represents a radical departure from the two previous generations. The earlier protocols were based on measurements using ion chambers with dose being derived by applying Bragg–Gray or Spencer–Attix cavity theory. In the first generation protocols, calibration laboratories provided exposure calibration factors for ion chambers in $^{60}$Co beams and users needed to look up a simple table of dose conversion factors versus nominal energy for either an x-ray or an electron beam.[1,2] The procedure was simple because there were no special considerations in these factors for either the type of chamber used or the actual quality of the beam. Omission of some of these considerations led to errors in beam calibrations of up to 5%. In the second generation of protocols, e.g., the AAPM's TG-21 protocol published in 1983,[3–5] many of these problems were reduced at the expense of added complexity. The accuracy of dose calibration was considerably better, but it required complex calculations, especially for the chamber-dependent factors and their variation with beam quality. These complexities themselves meant an increased potential for errors in the clinic.

The protocol being introduced, TG-51, still uses ion chambers as the basis for measurements, but requires absorbed dose to water calibration factors. As a result, it is conceptually easier to understand and simpler to implement than the earlier protocols. In the last decade, the major emphasis in primary standards laboratories has moved from standards for exposure or air kerma to those for absorbed dose to water since clinical reference dosimetry is directly related to this quantity, and also because primary standards for absorbed dose can be developed in accelerator beams, unlike exposure or air kerma standards. Standards for absorbed dose to water have an uncertainty ($1\sigma$) of less than 1% in $^{60}$Co and bremsstrahlung beams up to 25 MV (see, e.g., Refs. 6–9). It is appropriate to have a protocol that allows incorporation of this improved accuracy. These improvements are accomplished in this third generation protocol which is based on the use of ion chambers calibrated in terms of absorbed dose to water in a $^{60}$Co beam.[10–13]

Clinical reference dosimetry based on $^{60}$Co absorbed-dose calibration factors requires a quality conversion factor, denoted $k_Q$, and these factors have been calculated using Spencer–Attix cavity theory for the majority of cylindrical ionization chambers currently in clinical use for reference dosimetry. Determination of $k_Q$ factors for electron beams is more complex than for photon beams since there is a change in modality as well as energy, and some dependence on the gradient in the user's beam. The protocol has been written in such a way as to allow future incorporation of measurements with primary standards of absorbed dose in accelerator beams.

An important point in this protocol is that clinical reference dosimetry must be performed in a water phantom. Reference dosimetry measurements in plastics, including water-equivalent plastics, are not allowed. This is to ensure simplicity and accuracy in the protocol since the quantity of

interest is absorbed dose to water. This point does not preclude the use of plastic materials for more frequent quality assurance checks, provided a transfer factor has been established, but does require that in-water calibrations be performed at least annually.

This protocol also differs in one other significant respect from its predecessor. Whereas the TG-21 protocol combined both the theory and practical application in the same document, this protocol serves only as a ''how to'' document that will lead the medical physicist through all the steps necessary to perform clinical reference dosimetry for a given photon or electron beam. There are separate worksheets for photon and electron beam dosimetry.

Under the assumption that TG-21 correctly predicts the ratio of absorbed-dose to air-kerma calibration factors, it is not expected that implementation of this protocol will change the results of clinical reference dosimetry in photon beams by more than roughly 1% compared to those assigned following TG-21[3] for measurements in water. Slightly larger changes can be expected at $d_{\max}$ in electron beams because this protocol uses more accurate procedures regarding stopping-power ratios in realistic clinical electron beams and also takes into account the improvements provided by the TG-39 protocol for plane-parallel chambers.[14]

## II. NOTATION AND DEFINITIONS

All quantities shall be reported in SI units.

This protocol is based on the use of a set of physical data which is consistent with that used in US and Canadian primary standards laboratories. In particular, electron stopping powers are based on those developed at NIST and recommended in ICRU Report 37.[15]

$\%dd(10)_x$: the photon component of the photon beam percentage depth-dose at 10 cm depth in a $10\times10$ cm$^2$ field on the surface of a water phantom at an SSD of 100 cm (see Sec. VIII B).

$\%dd(10)$: the measured photon beam percentage depth-dose at 10 cm depth in a $10\times10$ cm$^2$ field on the surface of a water phantom at an SSD of 100 cm. $\%dd(10)$ includes the effects of electron contamination in the beam, whereas $\%dd(10)_x$ does not. $\%dd(10)$ is measured in an open beam.

$\%dd(10)_{Pb}$: same as $\%dd(10)$ except that a 1 mm lead foil is in place below the accelerator at about 50 cm from the phantom surface (or 30 cm if 50 cm clearance is not available).

clinical reference dosimetry: determination of absorbed dose to water per MU under reference conditions in the clinic.

$D_w^Q$: the absorbed dose to water for a given number of monitor units (or minutes for $^{60}$Co) from a radiation beam of quality $Q$. Unit: gray, Gy.

$d_{\max}$: the depth at which the absorbed dose to water (not ionization) is a maximum for a given beam. In photon beams it may include effects of electron contamination in the incident beam. Unit: cm.

$d_{\text{ref}}$: the reference depth for electron beams given as $d_{\text{ref}}=0.6R_{50}-0.1$, where $R_{50}$ is in cm. Unit: cm.

$I_{50}$: the depth in an electron beam at which the gradient-corrected ionization curve falls to 50% of its maximum (see Sec. VIII C). Unit: cm.

$k_Q$: the quality conversion factor, which accounts for the change in the absorbed-dose to water calibration factor between the beam quality of interest, $Q$, and the beam quality for which the absorbed-dose calibration factor applies (usually $^{60}$Co) [see Eq. (2)]. $k_Q$ is a function of the beam quality $Q$ [specified by $\%dd(10)_x$ or $R_{50}$] and is chamber dependent. For $^{60}$Co beams $k_Q=1.000$.

$k_{R_{50}}$: the component of $k_Q$ in an electron beam which is independent of the ionization gradient at the point of measurement (i.e., $k_Q=k_{R_{50}}P_{gr}^Q$, see Secs. IV and X B). $k_{R_{50}}$ is a function of the electron beam quality specified by $R_{50}$.

$k'_{R_{50}}$, $k_{\text{ecal}}$: the electron quality conversion factor and photon-electron conversion factor respectively. For electron beams, $k_{R_{50}}=k'_{R_{50}}k_{\text{ecal}}$ where $k_{\text{ecal}}$ is needed to convert $N_{D,w}^{^{60}\text{Co}}$ into an electron beam absorbed-dose calibration factor $N_{D,w}^{Q_{\text{ecal}}}$ for a selected beam quality $Q_{\text{ecal}}$ and $k'_{R_{50}}$ is needed to convert $N_{D,w}^{Q_{\text{ecal}}}$ into $N_{D,w}^{Q}$ for any beam quality $Q$ (see Secs. IV and X B). $k_{\text{ecal}}$ is fixed for a given chamber model and $k'_{R_{50}}$ is a function of the electron beam quality specified by $R_{50}$.

$M_{\text{raw}}(d)$: uncorrected ion chamber reading with the point of measurement of the ion chamber at a depth d in water, for a given number of monitor units (or minutes for $^{60}$Co). If no sign is indicated, the measurement is made collecting the same charge as during calibration (see Sec. VII A). If a sign is indicated ($+$ or $-$), it is the sign of the charge collected (see Sec. VII A). Unit: C (coulomb) or rdg (meter reading).

$M$: fully corrected ion chamber reading (see Sec. VII): corrected to the standard environmental conditions of temperature and pressure for which the ion chamber calibration factor applies; and also corrected for polarity effects, lack of complete ion collection efficiency, and electrometer accuracy. Unit: C or rdg.

*MU*: the number of monitor units (or minutes for $^{60}$Co) for which a given irradiation is performed.

$N_{D,w}$: the absorbed-dose to water calibration factor for an ion chamber located under reference conditions in a radiation beam. The absorbed dose measured is that at the chamber's point of measurement in the absence of the chamber. For a vented ion chamber the calibration factors from US and Canadian calibration laboratories apply for standard environmental conditions of temperature, pressure, and relative humidity. Calibration factors apply assuming the chamber reading corresponds to 100% charge collection efficiency [see Eq. (7)]. In contrast, calibration factors are usually for a stated polarity and corrections are needed if there is a significant polarity effect in the calibration beam (see Sec. VII A for how to handle this unusual case). Unit: Gy/C or Gy/rdg.

$N_{D,w}^Q$: the value of $N_{D,w}$ in a photon or electron beam of quality specified by $Q$.

$P$: air pressure inside ion chamber. In a vented chamber it is assumed to be the same as the local air pressure (see Sec.

VII C). Unit: kPa (kilopascals, 1 atmosphere = 760 mm of mercury = 101.33 kPa).

$P_{\text{elec}}$: the electrometer correction factor. If the electrometer is calibrated separately from the ion chamber, then $P_{\text{elec}}$ is the electrometer calibration factor which corrects the electrometer reading to true coulombs. $P_{\text{elec}}$ is considered 1.00 if the electrometer and ion chamber are calibrated as a unit. Unit: C/rdg or C/C.

$P_{\text{gr}}^{Q}$: the gradient correction factor is the component of $k_Q$ in an electron beam that is dependent on the ionization gradient at the point of measurement. For cylindrical chambers $P_{\text{gr}}^{Q}$ is a function of the radius of the cavity, $r_{\text{cav}}$ and the local gradient. $P_{\text{gr}}^{Q}$ is unity for plane-parallel chambers [see Secs. X B and IV and Eqs. (21) and (4)]. The equivalent factor in photon beams is accounted for within $k_Q$ since it is the same for all beams of a given photon beam quality.

$P_{\text{ion}}$: the recombination correction factor takes into account the incomplete collection of charge from an ion chamber (see Sec. VII D). Unlike the TG-21 protocol, this factor does not appear explicitly in the dose equation but it is now taken into account when determining the corrected charge reading $M$.

$P_{\text{pol}}$: the polarity correction factor which takes into account any polarity effect in the response of the ion chamber (see Sec. VII A).

$P_{\text{TP}}$: the temperature–pressure correction factor which makes the charge or measured current correspond to the standard environmental conditions for which the calibration factor applies (see Sec. VII C).

point of measurement: the point at which the absorbed dose is measured. For cylindrical ion chambers used for clinical reference dosimetry the point of measurement is on the central axis of the cavity at the center of the active volume of the cavity and for plane-parallel chambers the point of measurement is at the front (upstream side) of the air cavity at the center of the collecting region. When used in this specific sense, the phrase ''point of measurement'' is set out in the text as point of measurement.

$Q$: The beam quality in the user's photon or electron beam for which clinical reference dosimetry is to be performed. For photon beams it is given in terms of $\%dd(10)_{\text{x}}$ (see Sec. VIII B) and for electron beams, in terms of $R_{50}$ (see Sec. VIII C).

$Q_{\text{ecal}}$: an arbitrary electron beam quality taken as $R_{50}=7.5$ cm. It is introduced to simplify the factors needed in electron beam dosimetry (see Sec. IV).

$r_{\text{cav}}$: radius of the air cavity in a cylindrical ion chamber. Unit, cm. See Secs. VIII A and X B.

$R_{50}$: the depth in water in a $10\times10$ cm$^2$ or larger beam of electrons at an SSD of 100 cm at which the absorbed dose falls to 50% of the dose maximum (see Sec. VIII C). For beams with $R_{50}>$ 8.5 cm (i.e., with energy greater than roughly 20 MeV), a $20\times20$ cm$^2$ or greater field size is needed. Unit: cm.

rdg: the meter reading of an ion chamber in whatever units are on the scale.

reference conditions: defined conditions of depth, beam size and SSD/SAD for which clinical reference dosimetry is performed (see Secs. IX A and X A).

reference depth: the depth at which the point of measurement of the ion chamber is placed to measure the absorbed dose.

SSD/SAD: source-to-surface distance for electron or photon beams and source-to-axis distance for photon beams. This is usually a nominal distance since the position of the source is not well defined in many cases (see Sec. IX A). Unit: cm.

standard environmental conditions: conditions of temperature, pressure, and relative humidity for which ion chamber calibration factors apply. In the US and Canada these are temperature, $T_0=22\,^{\circ}$C, pressure, $P_0=101.33$ kPa, and relative humidity of the air in the ion chamber between 20% and 80% (see Sec. VII C).

$T$: temperature of the air inside an ion chamber, taken as the temperature of the surrounding water when in thermal equilibrium. Unit: °C (degree Celsius).

The new notation in this protocol may at first seem daunting. The following general observations may be helpful.

Beam quality is denoted by a $Q$ in the general case for both electron and photon beams. Two specific beam qualities that are referred to often are $^{60}$Co and $Q_{\text{ecal}}$. The beam quality specifiers used are $\%dd(10)_{\text{x}}$ for photon beams and $R_{50}$ for electron beams.

The various $k$ quality conversion factors all transform an absorbed-dose calibration factor from one quality to another as follows (these relationships are formally introduced below and this summary is here only as an *aide-memoire*). Note that the quality conversion factor, $k_Q$, is used to transform the $^{60}$Co absorbed-dose calibration factor to the corresponding factor in any beam quality $Q$ for electrons or photons. In contrast, the $k_{R_{50}}$ factors apply only to electron beams and in the general case require an additional gradient correction factor, hence the different notation.

$$N_{D,w}^{^{60}\text{Co}} \xrightarrow{k_Q} N_{D,w}^{Q} \quad \text{(photons or electrons)}$$

$$N_{D,w}^{^{60}\text{Co}} \xrightarrow{k_{R_{50}}} N_{D,w}^{Q} \quad \text{(electrons[a])}$$

$$N_{D,w}^{^{60}\text{Co}} \xrightarrow{k_{\text{ecal}}} N_{D,w}^{Q_{\text{ecal}}} \xrightarrow{k'_{R_{50}}} N_{D,w}^{Q} \quad \text{(electrons[a,b])}$$

[a]also need $P_{\text{gr}}^{Q}$ for cylindrical chambers.
[b]also need $P_{\text{gr}}^{Q_{\text{ecal}}}$ for cylindrical chambers.

Note that for electron beams $k_Q=P_{\text{gr}}^{Q}\,k_{R_{50}}$ and $k_{R_{50}}=k'_{R_{50}}k_{\text{ecal}}$.

## III. INTRODUCTION

This protocol prescribes a methodology for clinical reference dosimetry. It applies to photon beams with nominal energies between $^{60}$Co and 50 MV and electron beams with nominal energies between 4 and 50 MeV.

The protocol uses ion chambers calibrated in terms of absorbed dose to water in a $^{60}$Co beam.

The primary purpose of this dosimetry protocol is to ensure uniformity of reference dosimetry in external beam ra-

diation therapy with high-energy photons and electrons. To achieve this goal requires a common starting point and this is accomplished by starting with an ion chamber calibration factor which is directly traceable to national standards of absorbed dose to water maintained by Primary Standards Laboratories (National Institute of Standards and Technology, NIST, in the US, the National Research Council of Canada, NRCC, in Canada). Direct traceability is also achieved via calibration factors obtained from an Accredited Dosimetry Calibration Laboratory (ADCL).

## IV. GENERAL FORMALISM

Many of the data used in this protocol apply only under certain well-defined reference conditions. These conditions are specified below for photon and electron beams, and include such factors as the depth of measurement, field size, and source-to-surface distance, SSD. Also, throughout this protocol doses and charges are ''for a given number of monitor units (or minutes for $^{60}$Co),'' although this cumbersome phrase will not usually be included.

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 $Q$, then, under reference conditions:

$$D^{\mathrm{Q}}_w = M N^Q_{D,w} \quad \text{(Gy)}, \tag{1}$$

where $D^{\mathrm{Q}}_w$ is the absorbed dose to water (in Gy) at the point of measurement of the ion chamber when it is absent (i.e., at the reference depth); $M$ is the fully corrected electrometer reading in coulombs (C) or meter units (rdg) which has been corrected for ion recombination, polarity and electrometer calibration effects and corrected to standard environmental conditions of temperature and pressure (see Sec. VII); and the same or equivalent waterproofing sleeve is used as was used during the calibration (if needed). If an absorbed-dose calibration factor has been obtained for the beam quality of interest, this equation can be used directly and the next step in this protocol, to determine $k_Q$ (see below), can be bypassed.

More usually, it is expected that absorbed-dose calibration factors will be obtained for reference conditions in a $^{60}$Co beam, viz. $N^{^{60}\mathrm{Co}}_{D,w}$. In this case, define the quality conversion factor, $k_Q$, such that

$$N^Q_{D,w} = k_Q N^{^{60}\mathrm{Co}}_{D,w} \quad \text{(Gy/C or Gy/rdg)}, \tag{2}$$

i.e., $k_Q$ converts the absorbed-dose to water calibration factor for a $^{60}$Co beam into the calibration factor for an arbitrary beam of quality $Q$ which can be for photon or electron beams in general. The quality conversion factor $k_Q$ is chamber specific. Using $k_Q$, gives[10,12,13]

$$D^Q_w = M k_Q N^{^{60}\mathrm{Co}}_{D,w} \quad \text{(Gy)}. \tag{3}$$

For photon beams, this protocol provides values of $k_Q$ for most chambers used for reference dosimetry (Sec. IX B). Note that plane-parallel chambers are not included because there is insufficient information about wall correction factors in photon beams other than $^{60}$Co beams.

In general, for electron beams the quality conversion factor $k_Q$ contains two components, i.e.,

$$k_Q = P^Q_{\mathrm{gr}}\, k_{R_{50}}, \tag{4}$$

where $k_{R_{50}}$ is a chamber-specific factor which depends on the quality for which the absorbed-dose calibration factor was obtained and the user's beam quality, $Q$, as specified by $R_{50}$ (see Sec. VIII C), and $P^Q_{\mathrm{gr}}$ is necessary only for cylindrical chambers, to correct for gradient effects at the reference depth. The value of $P^Q_{\mathrm{gr}}$ depends on the radius of the chamber cavity and the ionization gradient at the point of measurement in the user's beam and must be measured by the user. This protocol provides a procedure for measuring $P^Q_{\mathrm{gr}}$ in the user's electron beam (as described in Sec. X B).

The factor $k_{R_{50}}$ is written as the product of two factors, viz.

$$k_{R_{50}} = k'_{R_{50}} k_{\mathrm{ecal}}. \tag{5}$$

The photon-electron conversion factor, $k_{\mathrm{ecal}}$, is fixed for a given chamber model and is just $k_{R_{50}}$ for an electron beam of quality $Q_{\mathrm{ecal}}$, i.e., the value needed to convert $N^{^{60}\mathrm{Co}}_{D,w}$ into $N^{Q_{\mathrm{ecal}}}_{D,w}$, the absorbed-dose calibration factor in an electron beam of quality $Q_{\mathrm{ecal}}$. The electron beam quality conversion factor, $k'_{R_{50}}$, is beam quality dependent and converts $N^{Q_{\mathrm{ecal}}}_{D,w}$ into $N^Q_{D,w}$. Thus, in an electron beam, the dose is given by

$$D^Q_w = M P^Q_{\mathrm{gr}}\, k'_{R_{50}} k_{\mathrm{ecal}}\, N^{^{60}\mathrm{Co}}_{D,w} \quad \text{(Gy)}. \tag{6}$$

The introduction of the photon-electron conversion factor, $k_{\mathrm{ecal}}$, appears quite arbitrary, but it is very useful since (i) it means the chamber-to-chamber variation of $k'_{R_{50}}$ is much less than that of $k_{R_{50}}$; (ii) it is a directly measurable quantity once primary standards for absorbed dose in electron beams are available; and (iii) it plays a very natural role when cross-calibrating plane-parallel chambers against calibrated cylindrical chambers (see Sec. X C).

Although the protocol allows and provides data to carry through the above approach using plane-parallel chambers, there is evidence that minor construction details significantly affect the response of these detectors in $^{60}$Co beams[16] and this makes measurements or calculations of $k_{\mathrm{ecal}}$ more uncertain. Therefore, the preferred choice is to cross calibrate them in high-energy electron beams against calibrated cylindrical chambers as recommended by TG-39[14] (see Sec. X C).

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 below 10 MeV but is deeper for higher-energy beams.[17] By going to this depth the protocol can make use of stopping-power ratios which account for the realistic nature of electron beams rather than assume they are mono-energetic and at the same time no longer requires stopping-power ratios tabulated as a function of depth and $R_{50}$ (or mean energy at the phantom surface).

To utilize this formalism one starts by obtaining an absorbed-dose to water calibration factor for an ion chamber in a $^{60}$Co beam as described in the next section and then

determines the quality conversion factor, $k_Q$, for the chamber being used. This first requires that one determine the beam quality, $Q$.

## V. OBTAINING AN ABSORBED-DOSE TO WATER CALIBRATION FACTOR

The first step in applying this protocol is to obtain an absorbed-dose to water calibration factor for the user's ion chamber when placed in a $^{60}$Co beam under reference conditions (specified in Sec. IX A). The absorbed-dose calibration factor is defined such that

$$N_{D,w}^{^{60}\mathrm{Co}} = \frac{D_w^{^{60}\mathrm{Co}}}{M} \quad (\mathrm{Gy/C\ or\ Gy/rdg}), \tag{7}$$

where $D_w^{^{60}\mathrm{Co}}$ 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. The calibration factor applies under standard environmental conditions of temperature, pressure, and relative humidity of the air in the ion chamber, viz. 22 °C, 101.33 kPa, and relative humidity between 20% and 80%, respectively (in the US and Canada). This calibration factor must be traceable to the user's national primary standard for absorbed dose to water. In practice, for most members of the AAPM, this means the calibration factor must be obtained from an ADCL in the US (traceable to NIST) or NRCC in Canada.

It is the responsibility of the clinical physicist to ensure that there are adequate, independent, and redundant checks in place to ensure that any problems with the ion chamber will be detected prior to the routine calibration.[18] Checks are achieved by use of check sources, by regular measurements in a $^{60}$Co beam, or by use of multiple independent dosimetry systems. With adequate and redundant checks in place, it is necessary to have the ion chamber calibrated when first purchased, when repaired, when the redundant checks suggest a need, or once every two years. The clinical physicist must perform at least two independent checks prior to sending a chamber for calibration and repeat the same checks when the chamber is returned to ensure that the chamber characteristics have not changed during transit and the calibration factor obtained applies to the chamber.

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.

### A. Chamber waterproofing

To follow this protocol a chamber is calibrated in water as well as used clinically in water. As a result, $^{60}$Co buildup caps are not needed. However, equivalent waterproofing techniques must be used for measurements in the user's beam and in the calibration laboratory. An inherently waterproof chamber avoids the complications of extra waterproofing sleeves and possible air gaps.

Chambers that are inherently waterproof will be calibrated in water without any extra waterproofing. It is the user's responsibility to ensure the integrity of inherent waterproofing by using the chamber in a water tank immediately prior to sending it for calibration. For nonwaterproof chambers the calibration laboratories will use their own thin-walled waterproofing sleeves to calibrate Farmer-like cylindrical chambers or they will use the clients waterproofing sleeve if it meets the criteria below. It is the responsibility of the clinical physicist to use a waterproofing sleeve which minimizes air gaps near the chamber wall ($\leqslant$0.2 mm) and it should be made of polymethylmethacrylate (PMMA) $\leqslant$1 mm thick. Another allowed option is to use a latex condom but users are urged to make sure talcum powder is not used in this case since the talcum can lead to problems with the ion chamber. Other materials are not recommended since discrepancies have been observed.[19–21] For other chamber types, the user should communicate with the calibration laboratory to ensure that the waterproofing sleeves used in the calibration laboratory, and in the user's beam, are similar and meet the criteria above. If the user's waterproofing sleeve meets the above criteria, then the effect of the sleeves in both the calibration lab and the clinic are negligible, as are any differences between them.

## VI. MEASUREMENT PHANTOMS

Clinical reference dosimetry must be performed in a water phantom with dimensions of at least $30\times30\times30$ cm$^3$. If the beam enters through the plastic wall of the water phantom and the wall is greater than 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. For a PMMA wall, in photon or electron beams the effective wall thickness is given by the measured thickness in cm times 1.12.[3,22]

## VII. CHARGE MEASUREMENT

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

$$M = P_{\mathrm{ion}} P_{\mathrm{TP}} P_{\mathrm{elec}} P_{\mathrm{pol}} M_{\mathrm{raw}} \quad (\mathrm{C\ or\ rdg}), \tag{8}$$

where $M_{\mathrm{raw}}$ is the raw ion chamber reading in coulombs, C, or the instrument's reading units (rdg); $P_{\mathrm{TP}}$ is the temperature–pressure correction which corrects the reading to the standard environmental conditions for which the ion chamber's calibration factor applies; $P_{\mathrm{ion}}$ corrects for incomplete ion collection efficiency; $P_{\mathrm{pol}}$ corrects for any polarity effects; and $P_{\mathrm{elec}}$ takes into account the electrometer's calibration factor if the electrometer and ion chamber are calibrated separately. In addition, any shutter timing error must be accounted for if needed (see, e.g., Ref. 23, p. 358, or TG-61[24]).

### A. Polarity corrections

Polarity effects[25–27] vary with beam quality and other conditions such as cable position. Therefore, it is necessary to correct for these effects by making measurements each time clinical reference dosimetry is performed.

To correct an ion chamber's raw reading for polarity effects one takes readings with both polarities applied and deduces $P_{\mathrm{pol}}$ from

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

where $M^{+}_{\text{raw}}$ is the reading when positive charge is collected, $M^{-}_{\text{raw}}$ is the reading when negative charge is collected, and $M_{\text{raw}}$ (one of $M^{+}_{\text{raw}}$ or $M^{-}_{\text{raw}}$) is the reading corresponding to the charge collected for the reference dosimetry measurements in the clinic and which should be the same as for the chamber calibration. In both cases, the sign of $M_{\text{raw}}$ must be used and usually $M^{+}_{\text{raw}}$ and $M^{-}_{\text{raw}}$ have opposite signs unless the background is large. Adequate time must be left after changing the sign of the voltage so that the ion chamber's reading has reached equilibrium.

In the unlikely event that the polarity correction is more than 0.3% different from unity in a photon beam of 6 MV or lower energy, then one must establish what the value of $P_{\text{pol}}$ is in the calibration laboratory's beam. This can be requested from the calibration laboratory or established by the clinical physicist using a $^{60}$Co source. Since calibration laboratories traditionally report the calibration factor for one polarity, if there is a significant polarity correction in the calibration beam, the user must use $N^{^{60}\text{Co}}_{D,w}/P^{^{60}\text{Co}}_{\text{pol}}$ everywhere in this protocol instead of $N^{^{60}\text{Co}}_{D,w}$.

### B. Electrometer correction factor

It is common practice in the US to calibrate ion chambers and electrometers separately. This is not essential and it is common practice in Canada to calibrate them as a unit. If the electrometer is calibrated separately from the ion chamber, the electrometer correction factor, $P_{\text{elec}}$, is just the electrometer calibration factor which corrects the electrometer reading to true coulombs. The electrometer calibration factor is obtained from an Accredited Dosimetry Calibration Laboratory. $P_{\text{elec}}$ is the electrometer correction factor which is applicable to the range being used on the electrometer. $P_{\text{elec}}$ is considered 1.00 if the electrometer and ion chamber are calibrated as a unit. It is also taken as 1.00 for cross-calibrated plane-parallel chambers since it cancels out of the final equations (see Sec. X C).

### C. Standard environmental conditions: Temperature, pressure, and relative humidity

Since calibration factors are given for standard environmental conditions of temperature at $T_0 = 22\,^{\circ}\text{C}$ and pressure at $P_0 = 101.33$ kPa (1 atmosphere), one corrects charge or meter readings to standard environmental conditions using

$$P_{\text{TP}} = \frac{273.2 + T}{273.2 + 22.0} \times \frac{101.33}{P}, \tag{10}$$

where $T$ is the temperature in degrees 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). Standard environmental conditions are different in some countries outside the US and Canada and the corresponding changes in Eq. (10) are necessary.

Chambers require time to reach thermal equilibrium with their surroundings. After inserting the ion chamber into the water tank it is necessary to ensure that this equilibrium is reached by waiting for changes in chamber output to become negligible. At this point, usually after 5 to 10 min,[28] one can assume that the temperature inside the ion chamber has reached the temperature of the water near the chamber in the phantom.

It is assumed that the relative humidity is always in the range of 20% to 80%. In this range, the error introduced by ignoring variations in relative humidity is $\pm 0.15\%$.[29]

Humid air may cause condensation inside the ion chamber volume and this can affect chamber response, especially for nylon-wall chambers[30] which therefore should not be used.

### D. Corrections for ion-chamber collection inefficiency

#### 1. General comments on $P_{ion}$

In this protocol, ion chamber readings in the user's beam must be corrected for lack of complete collection efficiency. This recombination correction factor is denoted $P_{\text{ion}}$ and the experimental methods for measuring it are discussed below. It must be emphasized that $P_{\text{ion}}$ is a function of the dose per pulse in accelerator beams 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.

This protocol is based on the definition of the calibration factor given in Eq. (7), which means that it applies when 100% of the ions created are collected. The correction to 100% ion collection at the time of chamber calibration is done at the calibration laboratory. The user must, however, explicitly include in Eq. (8), the recombination correction, $P_{\text{ion}}$, which applies in each of the user's beams.

The recombination corrections are well enough understood[31] that for small corrections they can be made accurately. However, if an ion chamber exhibits a correction factor, $P_{\text{ion}}$, greater than 1.05, the uncertainty in this correction becomes unacceptably large and another ion chamber with a smaller recombination effect should be used. Voltages should not be increased above normal operating voltages just to reduce $P_{\text{ion}}$ since there are indications in the literature that the assumptions in the standard theories break down at higher voltages.[32–36] In fact, the evidence suggests that lower voltages should be used as long as $P_{\text{ion}}$ values are acceptable. Despite these issues, the procedure recommended below is very similar to the TG-21 procedure since the above effects are believed to cause less than 0.5% errors at normal operating voltages of 300 V or less.

#### 2. Measuring $P_{ion}$

The standard two-voltage techniques for determining the $P_{\text{ion}}$ correction should be used. This involves measuring the charge produced by the ion chamber in the beam of interest when two different bias voltages are applied to the detector.

After changing the voltage it is necessary to wait for the chamber readings to come to equilibrium (usually several minutes, at least).

Let $V_H$ be the normal operating voltage for the detector (always the higher of the two voltages in these measurements) and $M^H_{\text{raw}}$ be the raw chamber reading with bias $V_H$. After measuring $M^H_{\text{raw}}$ reduce the bias voltage by at least a factor of 2 to $V_L$ and measure $M^L_{\text{raw}}$ once the chamber readings have reached equilibrium.

For continuous (i.e., $^{60}$Co) beams, the two voltage formula gives[37,38]

$$P_{\text{ion}}(V_H)=\frac{1.-(V_H/V_L)^2}{M^H_{\text{raw}}/M^L_{\text{raw}}-(V_H/V_L)^2}. \tag{11}$$

Equation (11) extracts an estimate of the general recombination in the continuous beam although initial recombination may dominate.

For pulsed or pulsed-swept beams with $P_{\text{ion}}<1.05$, i.e., where the linear form of the saturation curve holds,

$$P_{\text{ion}}(V_H)=\frac{1.-V_H/V_L}{M^H_{\text{raw}}/M^L_{\text{raw}}-V_H/V_L}. \tag{12}$$

Although the exact equations for pulsed or pulsed-swept beams are nonlinear,[38] Eq. (12) gives the same result as solving the nonlinear equations to within 0.2% and 0.4%, respectively, for a voltage ratio of 2 and 0.3% and 0.6% for a voltage ratio of 3 and is most inaccurate at the limiting value of $P_{\text{ion}}=1.05$. For larger values of the voltage ratio or values of $P_{\text{ion}}$ near 1.05 one may use the published programs or fits for the nonlinear equations.[5,38]

## VIII. 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, $k'_{R_{50}}$. For a $^{60}$Co beam the factor $k_Q=1.000$ by definition and hence there is no need for further beam quality specification. Beam quality must be measured each time clinical reference dosimetry is performed for accelerator beams. To do this, one needs to measure a parameter related to the central-axis depth-dose curves for the beam in question. Careful measurement of depth-dose curves is quite complex because various factors needed for converting depth-ionization curves to depth-dose curves change as a function of depth. Although this protocol is quite flexible about the SSD used when establishing the absorbed dose at the reference depth, nonetheless it is essential to use SSD=100 cm when establishing the beam quality for photon and electron beams. This is because $\%dd(10)$ and $R_{50}$ are functions of SSD whereas absorbed-dose calibration factors are not (for $10\times10\,\text{cm}^2$ fields).

### A. Accounting for gradient and depth of measurement effects

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 (as opposed to a depth-dose curve). Nonetheless, the effective point of measurement is upstream of the point of measurement (i.e., closer to the radiation source) due to the predominantly forward direction of the secondary electrons (since the primary beam enters the chamber at various distances upstream). This has an impact on the measurement of depth-ionization (and therefore depth-dose) curves and on the calculation of absolute dose from ionization measurements at the reference depth.

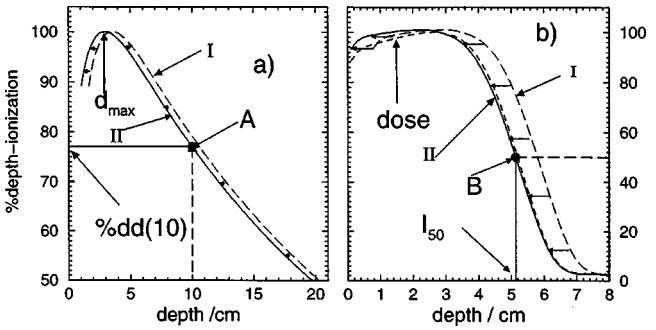


FIG. 1. Effect of shifting depth-ionization data measured with cylindrical chambers upstream by 0.6 $r_{\text{cav}}$ for photon beams [panel (a)] and 0.5 $r_{\text{cav}}$ for electron beams [panel (b)] (with $r_{\text{cav}}$ = 1.0 cm). The raw data are shown by curve I (long dashes) in both cases and the shifted data, which are taken as the depth-ionization curve, are shown by curve II (solid line). The value of the % ionization at point A (10 cm depth) in the photon beam gives $\%dd(10)$ and the depth at point B (solid curve, 50% ionization) in the electron beam gives $I_{50}$ from which $R_{50}$ can be determined (see Sec. VIII C). For the photon beams, curve II is effectively the percentage depth-dose curve. For the electron beams, curve II must be further corrected (see Sec. X D) to obtain the percentage depth-dose curve shown (short dashes—but this is not needed for application of the protocol).

When measuring central-axis depth-dose data with a cylindrical chamber, the effective point of measurement is made use of as follows. First, depth-ionization data are measured with the point of measurement identified as the assumed depth, as shown by curve I in Figs. 1(a) and 1(b). The entire curve is then shifted to shallower depths by a distance proportional to $r_{\text{cav}}$, the radius of the ionization chamber cavity, as shown by curves II in Figs. 1(a) and 1(b). For cylindrical and spherical chambers the shift is taken as $0.6r_{\text{cav}}$ for photon beams[35] and $0.5r_{\text{cav}}$ for electron beams.[22,39,40] The shifted curves are taken as the depth-ionization curves for cylindrical chambers. It is these depth-ionization curves that are used to determine the beam quality for both photons and electrons. Using these measurements as depth-ionization curves ignores any variations in $P_{\text{ion}}$ and $P_{\text{pol}}$ with depth[41] and for electron beams it also ignores 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.

For photon beams the variation in stopping-power ratio is negligible past $d_{\max}$ ($<0.1\%$[42]) 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 this protocol except to transfer the dose from $d_{ref}$ to $d_{max}$ if necessary (Sec. X D).

For plane-parallel chambers, the center of the front (upstream) face of the chamber air cavity is the point of measurement. This is traditionally taken as the effective point of measurement.[3,39] Therefore there is no shift in the depth-ionization curves for plane-parallel chambers and curves I and II are coincident and give the depth-ionization curve for the purposes of beam quality specification.

In contrast to the above, for measurements of absolute dose at the reference depth in both electron and photon beams, a cylindrical chamber's point of measurement (center of the chamber, Sec. II) is placed at the reference 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 $P_{gr}^{Q}$ for electrons. That is, the formalism of this protocol yields absorbed dose to water at the point occupied by the point of measurement after the chamber has been removed from the water.

### B. Beam-quality specification for photon beams

For the purposes of reference beam dosimetry, beam quality in accelerator 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). The value of $\%dd(10)_x$ is defined for a field size of $10\times10$ cm$^2$ at the phantom surface at an SSD of 100 cm. For $^{60}$Co beams $\%dd(10)_x$ is not required since $k_Q=1.000$ by definition.

At higher energies (about 10 MV and above), the electrons from the accelerator head may significantly affect the dose at $d_{max}$ and hence reduce the measured value of $\%dd(10)$. This electron contamination varies with machine type. However, it has been shown that placing a 1 mm thick lead foil just below the accelerator head reduces the effects of the electrons from the accelerator to a negligible level and calculations have been done which take into account the effect of the known electron contamination from the lead foil.[43,44] Thus the first step in specifying the photon beam quality for beams with energies of 10 MV or above is to measure the value of $\%dd(10)_{Pb}$ with a 1 mm lead foil positioned to intercept the beam completely (but remove it for the measurement of absorbed dose at the reference position). For beam energies below 10 MV the lead foil is not needed and one measures $\%dd(10)$ in the open beam.

If a 1 mm lead foil is being used, it should be placed about 50 cm from the phantom surface ($\pm5$ cm) in an otherwise open beam. Only if the accelerator construction does not permit a position near 50 cm (e.g., because of tertiary collimators), then the lead foil may be placed $30\pm1$ cm from the phantom surface. The exact thickness of the lead foil is not critical and a tolerance of $\pm20\%$ is acceptable.[43]

To measure $\%dd(10)_{Pb}$, with the lead foil in place (for 10 MV and above), or $\%dd(10)$ for lower-energy beams when the foil is not needed, an ion chamber should be used to generate the central-axis percentage depth-ionization curve measured in water [i.e., curve I in Fig. 1(a)] using a field size of $10\times10$ cm$^2$ at the phantom surface and an SSD of 100 cm. For cylindrical or spherical chambers, the measured depth-ionization data should be shifted upstream by $0.6r_{cav}$ to give curve II, the depth-ionization curve. For plane-parallel chambers no shift is needed, i.e., curves I and II are coincident. The percentage depth-ionization curve can be treated as the percentage depth-dose curve.

Next, locate point A at 10 cm depth on the percentage depth-dose curve [i.e., curve II in Fig. 1(a)]. This value is $\%dd(10)$ or $\%dd(10)_{Pb}$, the measured percentage depth-dose at 10 cm depth.

For beams with energies less than 10 MV, this value of $\%dd(10)$ measured in the open beam is the beam quality, $\%dd(10)_x$. For beam energies of 10 MV and above, 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 $50\pm5$ cm from the phantom surface by[43]

$$\%dd(10)_x=[0.8905+0.00150\%dd(10)_{Pb}]\%dd(10)_{Pb}$$
$$[\text{foil at } 50\ \text{cm}, \%dd(10)_{Pb}\geqslant 73\%], \qquad (13)$$

and, if the foil is placed at $30\pm1$ cm from the phantom surface, by

$$\%dd(10)_x=[0.8116+0.00264\%dd(10)_{Pb}]\%dd(10)_{Pb}$$
$$[\text{foil at } 30\ \text{cm}, \%dd(10)_{Pb}\geqslant 71\%]. \qquad (14)$$

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

The foil is only used when determining the beam quality specifier, $\%dd(10)_x$ and must be removed after the beam quality is determined.

There is also a general formula available to correct for electron contamination which can be used as an interim measure for machines with 45 cm or more clearance between the jaws and the phantom surface. For low-energy beams, i.e., for energies below 10 MV with $\%dd(10)\leqslant75\%$, $\%dd(10)_x=\%dd(10)$. For higher-energy beams the following applies up to $\%dd(10)=89\%$:

$$\%dd(10)_x=1.267\%dd(10)-20.0$$
$$[\text{for } 75\%<\%dd(10)\leqslant 89\%], \qquad (15)$$

where $\%dd(10)$ is measured as described above for an open beam. This formula is based on a global fit[45] to data in Fig. 7 of Ref. 46. For high-energy beams this global fit may cause errors in assigning $\%dd(10)_x$ of up to 2% in extreme cases,[46] which would lead to an error in $k_Q$, and hence the absorbed dose, of 0.4%.

### C. 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 $\geqslant10\times10$ cm$^2$ ($\geqslant20\times20$ cm$^2$ for $R_{50}>8.5$ cm, i.e.,

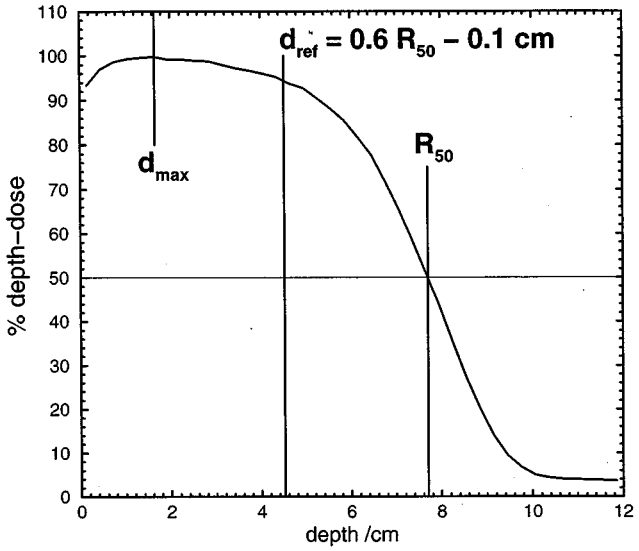


FIG. 2. Here $R_{50}$ is defined as the depth, in cm, at which the absorbed dose falls to 50% of its maximum value in a $\geq 10\times 10$ cm$^2$ ($\geq 20\times 20$ cm$^2$ for $R_{50} > 8.5$ cm) electron beam at an SSD of 100 cm. The depth for clinical reference dosimetry is $d_{\mathrm{ref}} = 0.6R_{50} - 0.1$ cm, in the same sized beam at an SSD between 90 and 110 cm. Note that for low-energy beams, $d_{\mathrm{ref}}$ is usually at $d_{\max}$.

$E > 20$ MeV) at an SSD of 100 cm. Figure 2 shows $R_{50}$ on a typical electron beam percentage depth-dose curve.

To determine $R_{50}$ one must first measure a central-axis depth-ionization curve in a water phantom at an SSD of 100 cm [curve I in Fig. 1(b)]. For cylindrical chambers, correct for gradient effects by shifting the curve upstream by $0.5\, r_{\mathrm{cav}}$ to give curve II.[22,39,40] For plane-parallel chambers no shift is needed. Curve II is taken as the depth-ionization curve.

Next, locate point B at the level of 50% of the maximum ionization on the depth-ionization curve corrected for gradient effects [i.e., curve II in Fig. 1(b)]. The depth of point B gives $I_{50}$. The beam quality specifier for the electron beam, $R_{50}$, is determined from the measured value of $I_{50}$ using[47,48]

$$R_{50} = 1.029 I_{50} - 0.06 \ \text{(cm)} \quad (\text{for } 2 \leq I_{50} \leq 10 \text{ cm}) \tag{16}$$

or

$$R_{50} = 1.059 I_{50} - 0.37 \ \text{(cm)} \quad (\text{for } I_{50} > 10 \text{ cm}). \tag{17}$$

A second alternative is to determine the percentage depth-dose curve using a good-quality diode detector which responds as a dose-detector in an electron beam,[22,49] although one must establish that this condition is fulfilled.[50] A third alternative is to convert the depth-ionization curve for an ion chamber to a percentage depth-dose curve (see Sec. X D).

## IX. PHOTON BEAM DOSIMETRY

In photon beams Eq. (3) 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 the user's photon beam of quality $Q$, specified by $\%dd(10)_x$, i.e.,

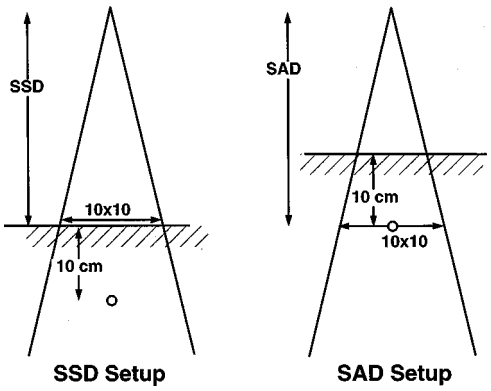


FIG. 3. Schematic of the SSD or SAD setups which may be used for photon beam reference dosimetry. In both cases the ion chamber is at a water equivalent depth of 10 cm in the water phantom. The actual value of SSD or SAD is that most useful in the clinic (expected to be about 100 cm).

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

### A. Reference conditions of depth, beam size, and source-surface/axis distance

Clinical reference dosimetry for photon beams is performed in an open beam (i.e., without trays, wedges, lead filters, or blocks) with the point of measurement of the cylindrical ion chamber placed at the reference depth which is at a water-equivalent depth of 10 cm in a water phantom (see Sec. VI for corrections if there is a wall in the path of the beam). Either an SSD or an SAD setup can be used (at the normal clinical distance, see Fig. 3). The field size is $10\times 10$ 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.

In calibration laboratories, the traditional reference depth for $^{60}$Co beams is 5 g/cm$^2$. The difference between an ion chamber's calibration factor determined at this depth versus one determined at a depth of 10 g/cm$^2$ is negligible,[42] and hence the calibration factor for a depth of 5 g/cm$^2$ can be used.

Note that although the reference conditions for measurement of the dose are quite flexible, those for the specification of beam quality are not and must be at SSD=100 cm (see Sec. VIII).

### B. Absorbed dose to water in clinical photon beams

To use Eq. (3) one needs a value of $k_Q$. For $^{60}$Co beams $k_Q = 1.000$. Figure 4 presents calculated values of $k_Q$ in accelerator beams as a function of $\%dd(10)_x$ for cylindrical ion chambers commonly used for reference dosimetry. Alternatively, values for specific chambers can be selected from Table I which contains values for the same cylindrical chambers, calculated as described by Rogers[45] with a minor update.[51] Note that plane-parallel chambers are not included because there is insufficient information about wall correction factors in photon beams other than $^{60}$Co.

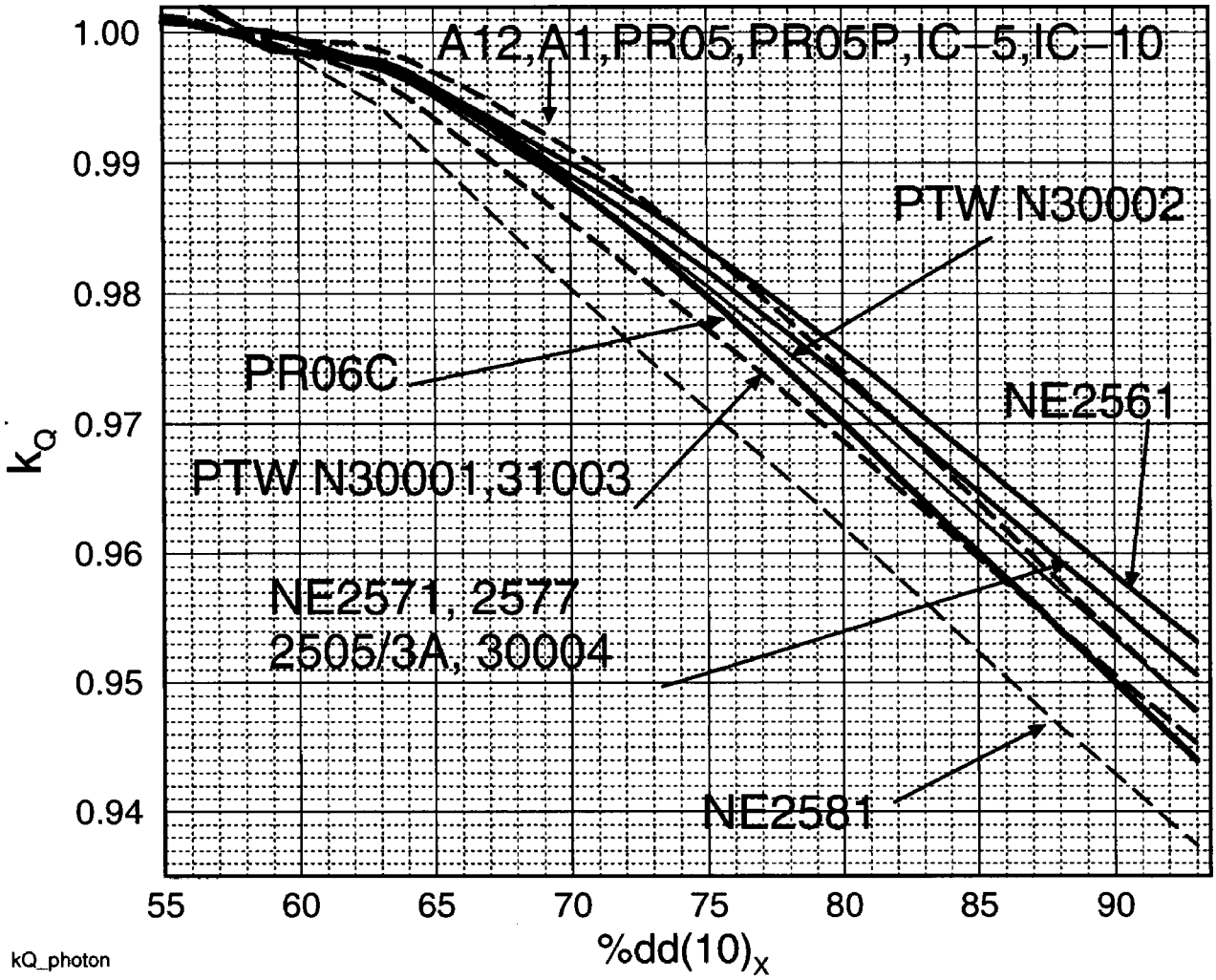


FIG. 4. Values of $k_Q$ at 10 cm depth in accelerator photon beams as a function of $\%dd(10)_x$ for cylindrical ion chambers commonly used for clinical reference dosimetry. When values were the same within 0.1%, only one curve is shown. Explicit values are given in Table I, as is a list of equivalent chambers. For $^{60}$Co beams, $k_Q = 1.000$.

TABLE I. Values of $k_Q$ for accelerator photon beams as a function of $\%dd(10)_x$ for cylindrical ion chambers commonly used for clinical reference dosimetry. Values calculated as described in Refs. 45 and 51. The tabulated values can be interpolated linearly in $\%dd(10)_x$. The ion chamber specifications used in these calculations are found in Table III. Figure 4 presents the same data within 0.1%. For $^{60}$Co beams, $k_Q = 1.000$ by definition.

| | $k_Q$ | | | | | |
|---|---|---|---|---|---|---|
| | $\%dd(10)_x$ | | | | | |
| Ion chamber | 58.0 | 63.0 | 66.0 | 71.0 | 81.0 | 93.0 |
| Capintec PR-05/PR-05P | 0.999 | 0.997 | 0.995 | 0.990 | 0.972 | 0.948 |
| Capintec PR-06C/G 0.6cc Farmer | 1.000 | 0.998 | 0.994 | 0.987 | 0.968 | 0.944 |
| Exradin A1 Shonka[a] | 0.999 | 0.998 | 0.996 | 0.990 | 0.972 | 0.948 |
| Exradin A12 Farmer | 1.000 | 0.999 | 0.996 | 0.990 | 0.972 | 0.948 |
| NE2505/3,3A 0.6cc Farmer | 1.000 | 0.998 | 0.995 | 0.988 | 0.972 | 0.951 |
| NE2561 0.3cc NPL Sec. Std[b] | 1.000 | 0.998 | 0.995 | 0.989 | 0.974 | 0.953 |
| NE2571 0.6cc Farmer | 1.000 | 0.998 | 0.995 | 0.988 | 0.972 | 0.951 |
| NE2577 0.2cc | 1.000 | 0.998 | 0.995 | 0.988 | 0.972 | 0.951 |
| NE2581 0.6cc robust Farmer | 1.000 | 0.994 | 0.988 | 0.979 | 0.960 | 0.937 |
| PTW N30001 0.6cc Farmer[c] | 1.000 | 0.996 | 0.992 | 0.984 | 0.967 | 0.945 |
| PTW N30002 0.6cc all Graphite | 1.000 | 0.997 | 0.994 | 0.987 | 0.970 | 0.948 |
| PTW N30004 0.6cc Graphite | 1.000 | 0.998 | 0.995 | 0.988 | 0.973 | 0.952 |
| PTW 31003 0.3cc waterproof[d] | 1.000 | 0.996 | 0.992 | 0.984 | 0.967 | 0.946 |
| Wellhofer IC-10/IC-5 | 1.000 | 0.999 | 0.996 | 0.989 | 0.971 | 0.946 |

[a]The cavity radius of the A1 here is 2 mm although in the past Exradin has designated chambers with another radius as A1.
[b]The NE2611 has replaced the equivalent NE2561.
[c]PTW N30001 is equivalent to the PTW N23333 it replaced.
[d]PTW N31003 is equivalent to the PTW N233641 it replaced.

TABLE II. Values of the photon-electron conversion factor, $k_{ecal}$, for plane-parallel chambers, calculated as described in Ref. 52 and adopting a beam quality $Q_{ecal}$ of $R_{50}=7.5$ cm. Section X C recommends using a cross calibration technique, if possible, to obtain $k_{ecal}N_{D,w}^{^{60}Co}$. However, if not possible, these values of $k_{ecal}$ may be used in Eq. (6) along with a $^{60}$Co calibration factor, $N_{D,w}^{^{60}Co}$.

| 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 |

### C. 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 using one of two methods. For SSD setups the clinical percentage depth-dose curves are used. For SAD setups the clinical tissue-phantom ratio (TPR) curves are used unless one wants the dose at $d_{max}$. In such situations the clinical tissue-maximum ratio (TMR) curves are used.

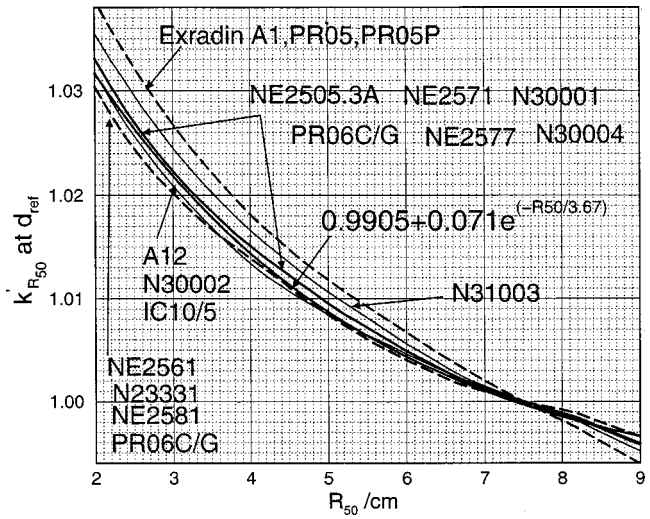


FIG. 5. Calculated values of $k'_{R_{50}}$ at $d_{ref}$ as a function of $R_{50}$ for several common cylindrical ion chambers. These values can be used with Eq. (6) (with a measured value of $P_{gr}^{Q}$ and a $k_{ecal}$ value from Table III) to determine the absorbed dose to water at the reference depth of $d_{ref}=0.6R_{50}-0.1$ cm.

## X. ELECTRON BEAM DOSIMETRY

Equation (6) gives the absorbed dose to water under reference conditions for the same number of monitor units as

TABLE III. Values of the photon-electron conversion factor, $k_{ecal}$, for commercial cylindrical chambers, calculated as described in Ref. 52 and adopting a beam quality $Q_{ecal}$ of $R_{50}=7.5$ cm.

| | | Wall | | | |
|---|---|---|---|---|---|
| Chamber | $k_{ecal}$ | Material | Thickness g/cm$^2$ | Cavity radius $r_{cav}$ (cm) | Al electrode diameter (mm) |
| 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.

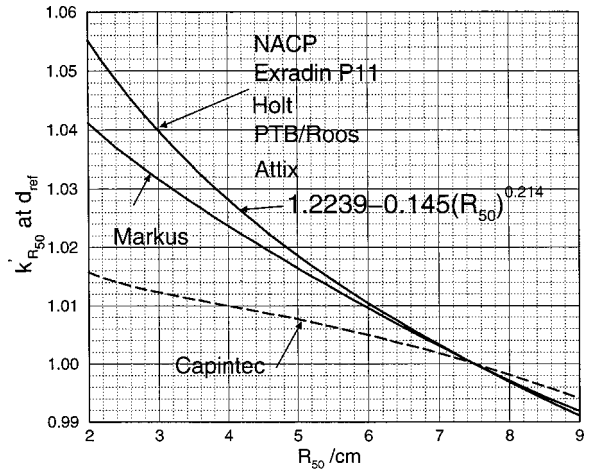


FIG. 6. Calculated values of $k'_{R_{50}}$ at $d_{\mathrm{ref}}$ as a function of $R_{50}$ for several common plane-parallel chambers. Note that the values for the five well-guarded chambers lie on the same line in the figure. These values can be used with Eq. (6) (with $P^Q_{\mathrm{gr}}=1.0$) to determine the absorbed dose to water at the reference depth of $d_{\mathrm{ref}}=0.6R_{50}-0.1$ cm.

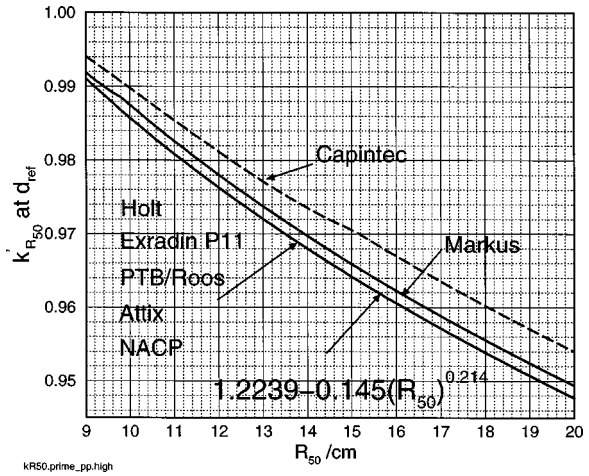


FIG. 8. Calculated values of $k'_{R_{50}}$ at $d_{\mathrm{ref}}$ for high-energy electron beams, as a function of $R_{50}$ for plane-parallel chambers. Note that the values for the five well-guarded chambers lie on the same line in the figure. These values can be used with Eq. (6) (with $P^Q_{\mathrm{gr}}=1.0$ and a $k_{\mathrm{ecal}}$ value from Table II) to determine the absorbed dose to water at the reference depth of $d_{\mathrm{ref}}=0.6R_{50}-0.1$ cm.

used to measure the charge $M$, at the point of measurement of the ion chamber, in an electron beam of quality $Q$, specified by $R_{50}$, i.e.,

$$D^Q_w = M P^Q_{\mathrm{gr}}\, k'_{R_{50}} k_{\mathrm{ecal}} N^{60\mathrm{Co}}_{D,w} \quad (\mathrm{Gy}).$$

For electron beams with $R_{50}\leqslant 4.3$ 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 $R_{50}\leqslant 2.6$ cm (incident energies of 6 MeV or less).

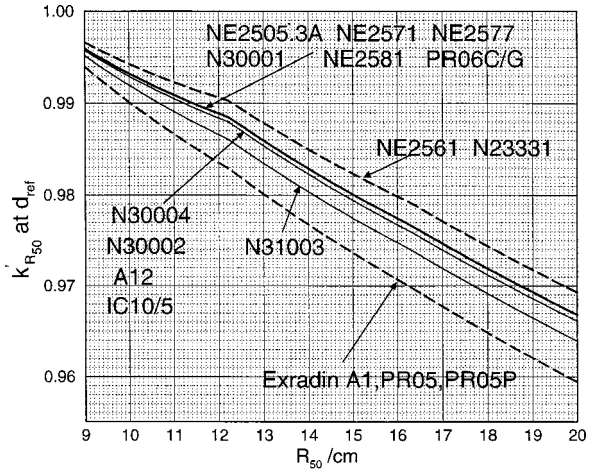


FIG. 7. Calculated values of $k'_{R_{50}}$ at $d_{\mathrm{ref}}$ for high-energy electron beams, as a function of $R_{50}$ for cylindrical ion chambers. These values can be used with Eq. (6) (with a measured value of $P^Q_{\mathrm{gr}}$ and a $k_{\mathrm{ecal}}$ value from Table III) to determine the absorbed dose to water at the reference depth of $d_{\mathrm{ref}}=0.6R_{50}-0.1$ cm.

### A. Reference conditions of depth, beam size, and source-surface distance

Clinical reference dosimetry for electron beams is performed in an open beam at the reference depth which is at a water-equivalent depth of[17]

$$d_{\mathrm{ref}}=0.6R_{50}-0.1 \quad (\mathrm{cm}). \tag{18}$$

See Sec. VI for corrections to the depth to take into account tank walls which may be in the path of the beam. The point of measurement of the ion chamber is placed at $d_{\mathrm{ref}}$ (i.e., the central axis of cylindrical chambers or the front face of the air cavity for plane-parallel chambers). For beams with $R_{50}\leqslant 8.5$ cm ($E\leqslant 20$ MeV), the field size is $\geqslant 10\times 10$ cm$^2$ at the phantom surface and for higher-energy beams it is $\geqslant 20\times 20$ cm$^2$.

Clinical reference dosimetry may be performed with an SSD from 90 to 110 cm. The underlying Monte Carlo calculations of stopping-power ratios were done for SSD=100 cm, but changes of up to 10 cm from this SSD do not affect the parameters used in the protocol.

### B. Absorbed dose to water in clinical electron beams

In electron beams, Eq. (6) is used to establish the absorbed dose to water. To use this equation one needs the values of the factors $P^Q_{\mathrm{gr}}$, $k'_{R_{50}}$, and $k_{\mathrm{ecal}}$. The values of $k_{\mathrm{ecal}}$ for a number of ion chambers are given in Tables II and III.[52] The selection of the beam quality $Q_{\mathrm{ecal}}$ are arbitrary and has been taken as $R_{50}=7.5$ cm for the purposes of this protocol.

Figure 5 presents calculated values for $k'_{R_{50}}$ for cylindrical ion chambers used for clinical reference dosimetry in electron beams with energies up to about 21 MeV and Fig. 6 presents $k'_{R_{50}}$ values for plane-parallel chambers.[52] For higher-energy electron beams, the corresponding data are presented in Figs. 7 and 8. For Farmer-like cylindrical cham-

bers the following expression can be used for $2 \leqslant R_{50} \leqslant 9$ cm with a maximum error of 0.2%:[52]

$$k'_{R_{50}}(\text{cyl}) = 0.9905 + 0.0710 e^{(-R_{50}/3.67)}. \quad (19)$$

For well-guarded plane-parallel chambers, the following expression is an analytic representation of the curve shown in Figs. 6 and 8, i.e., for $2 \leqslant R_{50} \leqslant 20$ cm:

$$k'_{R_{50}}(\text{pp}) = 1.2239 - 0.145(R_{50})^{0.214}. \quad (20)$$

The correction for gradient effects (i.e., $P_{\text{gr}}^{Q}$) 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 about 10 MeV. For cylindrical chambers $P_{\text{gr}}^{Q}$ is determined as[22,39]

$$P_{\text{gr}}^{Q} = \frac{M_{\text{raw}}(d_{\text{ref}} + 0.5 r_{\text{cav}})}{M_{\text{raw}}(d_{\text{ref}})} \text{ (for cylindrical chambers)}, \quad (21)$$

where $r_{\text{cav}}$ is the radius of the chamber's cavity in cm and $M_{\text{raw}}(d_{\text{ref}} + 0.5 r_{\text{cav}})/M_{\text{raw}}(d_{\text{ref}})$ is the ratio of the integrated charges or ionization currents with the central axis of the chamber at $d_{\text{ref}} + 0.5 r_{\text{cav}}$ and $d_{\text{ref}}$. This procedure is equivalent to making the measurement at the ''effective point of measurement,''[22,39] but the present formalism is adopted to facilitate future utilization of primary standards of absorbed dose to water in electron beams. Note that $P_{\text{gr}}^{Q}$ is less than 1 for $d_{\text{ref}} > (d_{\max} + 0.5 r_{\text{cav}})$.

### C. Use of plane-parallel chambers

For electron beam dosimetry this protocol allows for the use of plane-parallel chambers which have been 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,[16] it is recommended that, when possible, plane-parallel chambers be calibrated against calibrated cylindrical chambers in a high-energy electron beam, as recommended in TG-21[3] and TG-39.[14]

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 $d_{\text{ref}}$. While measuring with the cylindrical chamber, $P_{\text{gr}}^{Q}$ is measured as described above [see Eq. (21)]. From these measurements the product of $k_{\text{ecal}} N_{D,w}^{^{60}\text{Co}}$ is determined for the plane-parallel chamber as

$$(k_{\text{ecal}} N_{D,w}^{^{60}\text{Co}})^{\text{pp}} = \frac{(D_w)^{\text{cyl}}}{(M k'_{R_{50}})^{\text{pp}}} = \frac{(M P_{\text{gr}}^{Q} k'_{R_{50}} k_{\text{ecal}} N_{D,w}^{^{60}\text{Co}})^{\text{cyl}}}{(M k'_{R_{50}})^{\text{pp}}} \text{ (Gy/C)}. \quad (22)$$

This product is then used in Eq. (6), thereby avoiding the need for obtaining the $^{60}$Co absorbed-dose calibration factor for the plane-parallel chamber.

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

This protocol provides the reference dose at a depth of $d_{\text{ref}}$ 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 $d_{\text{ref}}$. Methods for measuring electron-beam percentage depth-dose curves are given in TG-25.[22] These procedures require stopping-power ratios when ion chambers are used and in TG-25 these are presented for mono-energetic electron beams. In TG-51, stopping-power ratios for realistic electron beams have been used and these differ from the mono-energetic stopping-power ratios. To extract the dose maximum in a completely consistent manner, the expression presented by Burns *et al.*[17] for stopping-power ratios in realistic electron beams as a function of $R_{50}$ and depth should be used to determine the clinical depth-dose data since they are consistent with the values used here (a FORTRAN routine is available at http://www.irs.inms.nrc.ca/inms/irs/papers/SPRR50/node12.html). Measuring depth-dose curves for electron beams also requires corrections for variations in $P_{\text{repl}}$ according to TG-25.[22] This variation can be significant for cylindrical chambers although there is no variation for well-guarded plane-parallel chambers.

## XI. USING OTHER ION CHAMBERS

This protocol provides $k_Q$ data for the vast majority of chambers used in clinical reference dosimetry in North America as evidenced by the data on ADCL calibrations. However, 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%. 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.

## ACKNOWLEDGMENTS

The members of the task group would like to thank the members of the RTC over the years in which this protocol was developed for their helpful comments and suggestions and, in particular, the 1998 members for their very helpful reviews. We also thank Alan Nahum of the Royal Marsden Hospital in Sutton, UK, and David Burns of the BIPM in Paris for detailed external reviews on behalf of the RTC and Jan Seuntjens of NRC Canada for helpful comments on many versions of the protocol. We also wish to acknowledge the contributions of Herb Attix who was involved with the early development of this protocol and the anonymous journal referee who provided thoughtful comments. Finally, we thank the members of the ADCL Subcommittee of the RTC for their substantial efforts to put in place a system for absorbed-dose calibrations and their helpful inputs to the protocol.

# TG–51 Worksheet A: Photon Beams

1. Site data
   - Institution: _____
   - Physicist: _____
   - Date: _____
   - Accel or $^{60}$Co Mfr: _____
   - Model &serial number: _____
   - Nominal photon energy/beam identifier: _____ MV
2. Instrumentation
   - a. Chamber model: _____
     - Serial number: _____
     - cavity inner radius ($r_{cav}$,Table III): _____ cm
     - Waterproof: yes☐ no☐
       - If no, is waterproofing $\leq 1$ mm PMMA or thin latex?: yes☐ no☐
   - b. Electrometer model: _____
     - Serial number: _____
     - i. $P_{elec}$,electrom. corr factor(Sec.VII.B): _____ C/C or C/rdg.
   - c. Calibration Factor $N_{D,w}^{^{60}Co}$ (Sec.V): _____ Gy/C (or Gy/rdg)
     - Date of report (not to exceed 2 years): _____
3. Measurement Conditions ($10\times10$cm$^2$, point of measurement at 10 cm depth (water equivalent))
   - a. Distance (SSD or SAD): _____ cm SAD☐ or SSD☐
   - b. Field size: _____ cm$^2$
     - on surface(SSD setup): ☐
     - at detector(SAD setup): ☐
   - c. Number of monitor units: _____ MU (min for $^{60}$Co)
4. Beam Quality (Sec.VIII.B –not needed for $^{60}$Co)
   - If energy $< 10$ MV, use no lead foil.
     - Measure $\%dd(10)$ [% depth-dose at 10 cm depth for curve shifted upstream by 0.6 $r_{cav}$]
     - Field size $10\times10$cm$^2$ on surface,SSD=100 cm: yes☐ no☐
     - a. $\%dd(10)_x = \%dd(10)$ _____
   - If energy $\geq 10$ MV
     - Distance of 1 mm lead foil from phantom surface 50±5cm☐ 30±1cm☐
     - Measure $\%dd(10)_{Pb}$ [% depth-dose at 10 cm depth for curve shifted upstream by 0.6 $r_{cav}$]
     - Field size $10\times10$cm$^2$ on surface,SSD=100 cm: yes☐ no☐
     - $\%dd(10)_{Pb}$ (includes $e^-$ contamination): _____

   50 cm: $\%dd(10)_x = [0.8905 + 0.00150\%dd(10)_{Pb}]\,\%dd(10)_{Pb}$ $[\%dd(10)_{Pb} \geq 73\%]$ Eq.(13)
   30 cm: $\%dd(10)_x = [0.8116 + 0.00264\%dd(10)_{Pb}]\,\%dd(10)_{Pb}$ $[\%dd(10)_{Pb} \geq 71\%]$ Eq.(14)
   If $\%dd(10)_{Pb} < 71\%$ (30cm) or 73%(50cm): $\%dd(10)_x = \%dd(10)_{Pb}$
   - b. $\%dd(10)_x$ (for open beam): _____
   - Has lead foil been removed? yes☐ no☐

## Worksheet A: Photon Beams (cont)

4.(cont): Interim alternative for energy > 10 MV & with ≥45 cm clearance: using no lead foil
Measure $\%dd(10)$ [% depth-dose at 10 cm depth for curve shifted upstream by 0.6 $r_{cav}$]
$\%dd(10)$: _____

$\%dd(10)_x = 1.267\,(\%dd(10)) - 20.0$ [for $75\% < \%dd(10) \leq 89\%$]

c. $\%dd(10)_x =$ _____

5. Determination of $k_Q$ (Sec.IX.B)
Chamber model used to get $k_Q$: _____
a. $\%dd(10)_x$ (from 4, above): _____
b. $k_Q$ [Table I or Fig 4 ]: _____

6. Temperature/Pressure Correction (Sec.VII.C)
a. Temperature: _____ °C
b. Pressure: _____ kPa [=mmHg·$\frac{101.33}{760.}$]
c. $P_{TP}$: _____ $\left[Eq.(10) = \left(\frac{273.2+6a}{295.2}\right)\left(\frac{101.33}{6b}\right)\right]$

7. Polarity Correction (Sec.VII.A)
$M^+_{raw}$: _____ C or rdg
$M^-_{raw}$: _____ C or rdg
a. $M_{raw}$ (for polarity of calibration): _____ C or rdg
b. $P_{pol}$: _____ $\left[Eq.(9) = \left|\frac{(M^+_{raw}-M^-_{raw})}{2M_{raw}}\right|\right]$

8. $P_{ion}$ measurements (Sec.VII.D.2)
Operating voltage = $V_H$: _____ V
Lower voltage $V_L$: _____ V
$M^H_{raw}$: _____ C or rdg
$M^L_{raw}$: _____ C or rdg
$^{60}$Co treated as general recombination
a. $P_{ion}(V_H)$ (Eq.(11)): _____ $\left[\left(1. - \left(\frac{V_H}{V_L}\right)^2\right) \Big/ \left(\frac{M^H_{raw}}{M^L_{raw}} - \left(\frac{V_H}{V_L}\right)\right)\right.$
Pulsed/swept beams
b. $P_{ion}(V_H)$ (Eq.(12)) _____ $\left[\left(1. - \frac{V_H}{V_L}\right) \Big/ \left(\frac{M^H_{raw}}{M^L_{raw}} - \frac{V_H}{V_L}\right)\right]$
If $P_{ion} > 1.05$, another ion chamber should be used.

9. Corrected ion. ch. rdg. $M$ (Sec.VII) at 10 cm depth, water equivalent
$$M = P_{ion}P_{TP}P_{elec}P_{pol}M_{raw} = [8(a \text{ or } b) \cdot 6c \cdot 2bi \cdot 7b \cdot 7a]$$
Fully corrected $M$(Eq.(8)): _____ C or rdg

10. Dose to water at 10 cm depth: $D^Q_w = Mk_QN^{^{60}Co}_{D,w} = [9 \cdot 5b \cdot 2c]$ Eq.(3)
a. Dose to water at 10 cm depth= _____ Gy
b. Dose / MU(or min,$^{60}$Co) at 10 cm depth | | Gy/MU(or min) | $[10a/3c]$

11. Dose to water/MU(or min,$^{60}$Co) at $d_{max}$ (if relevant locally)
a. Clinical $\%dd(10)$ for SSD setup / 100.: _____
or Clinical TMR(10,10×10) for SAD setup: _____
b. Dose / MU(or min,$^{60}$Co) at $d_{max}$: _____ Gy/MU(or min) $[10b/(11a)]$

# TG–51 Worksheet B: Electron Beams – Cylindrical Chambers

For electrons with $R_{50} \geq$2.6 cm (energies $>$ 6 MeV) only and preferably $\geq$ 4.3 cm (10 MeV).

1. Site data
   - Institution: _____
   - Physicist: _____
   - Date: _____
   - Accel Mfr: _____
   - Model &serial number: _____
   - Nominal electron energy/beam identifier: _____ MeV
2. Instrumentation
   - a. Chamber model: _____
     - Serial number: _____
     - cavity inner radius ($r_{cav}$,Table III): _____ cm
     - Waterproof: yes☐ no☐
       - If no, is waterproofing $\leq$ 1 mm PMMA or thin latex?: yes☐ no☐
   - b. Electrometer model: _____
     - Serial number: _____
     - i. $P_{elec}$,electrom. corr factor(Sec.VII.B): _____ C/C or C/rdg.
   - c. Calibration Factor $N_{D,w}^{^{60}Co}$ (Sec.V): _____ Gy/C (or Gy/rdg)
     - Date of report (not to exceed 2 years): _____
3. Measurement Conditions (central axis of chamber at $d_{ref}$, Sec.X.A)
   - a. Distance SSD: _____ cm
   - b. Field Size on surface: _____ $cm^2$
   - c. Number of monitor units: _____ MU
4. Beam Quality (Sec.VIII.C)

   Measure $I_{50}$ by measuring depth-ionization curve and, for cylindrical chambers only, shifting curve upstream by 0.5 $r_{cav}$

   $I_{50}$: _____ cm

   a.i. If $2 \leq I_{50} \leq 10$ cm:

   $R_{50} = 1.029 I_{50} - 0.06$ _____ cm

   ii. If $I_{50} > 10$ cm:

   $R_{50} = 1.059 I_{50} - 0.37$ _____ cm

   b. Reference depth $d_{ref} = 0.6 R_{50} - 0.1$ _____ cm (water equivalent)

## Worksheet B: Electron Beams - Cylindrical Chambers (cont)

5. Determination of $k_{\text{ecal}}$ and $k'_{R_{50}}$
   Chamber model used to get $k_{\text{ecal}}$: _____
   a. $k_{\text{ecal}}$ _____ [Table III]

   b. i. $k'_{R_{50}}$ from figures: _____ [Fig 5 or 7]
   or: ii. $k'_{R_{50}}$ from analytic expression for Farmer-like cylindrical chambers
   : $k'_{R_{50}} = 0.9905 + 0.071e^{(-R_{50}/3.67)}$ _____ [Eq.(19) $2 \le R_{50} \le 9$cm]

6. Temperature/Pressure Correction (Sec.VII.C)
   a. Temperature: _____ °C
   b. Pressure: _____ kPa [=mmHg·$\frac{101.33}{760.}$]
   c. $P_{TP}$: _____ $\left[Eq.(10) = \left(\frac{273.2+6a}{295.2}\right)\left(\frac{101.33}{6b}\right)\right]$

7. Polarity Correction (Sec.VII.A)
   $M^{+}_{\text{raw}}$: _____ C or rdg
   $M^{-}_{\text{raw}}$: _____ C or rdg
   a. $M_{\text{raw}}$ (for polarity of calibration): _____ C or rdg
   b. $P_{\text{pol}}$: _____ $\left[Eq.(9) = \left|\frac{(M^{+}_{\text{raw}} - M^{-}_{\text{raw}})}{2M_{\text{raw}}}\right|\right]$

8. $P_{\text{ion}}$ measurements (Sec.VII.D.2)
   Operating voltage $= V_H$: _____ V
   Lower voltage $V_L$: _____ V
   $M^{H}_{\text{raw}}$: _____ C or rdg
   $M^{L}_{\text{raw}}$: _____ C or rdg

   $P_{\text{ion}}(V_H)$ (pulsed/swept beam, Eq.(12)): _____ $\left[\left(1. - \frac{V_H}{V_L}\right) \Big/ \left(\frac{M^{H}_{\text{raw}}}{M^{L}_{\text{raw}}} - \frac{V_H}{V_L}\right)\right]$
   If $P_{\text{ion}} > 1.05$, another ion chamber should be used.

9. Corrected ion. ch. rdg. $M$ (Sec.VII) at $d_{\text{ref}}$
   $$M = P_{\text{ion}}P_{TP}P_{\text{elec}}P_{\text{pol}}M_{\text{raw}} = [8 \cdot 6c \cdot 2bi \cdot 7b \cdot 7a]$$
   Fully corrected $M$(Eq.(8)): _____ C or rdg

10. Dose to water at reference depth, $d_{\text{ref}}$: $D^{Q}_{w} = MP^{Q}_{gr}\ k'_{R_{50}}\ k_{\text{ecal}}N^{^{60}Co}_{D,w} = [9 \cdot 10a \cdot 5b \cdot 5a \cdot 2c\ ]$
    a. $P^{Q}_{gr}(cyl) = \frac{M_{\text{raw}}(d_{\text{ref}}+0.5r_{\text{cav}})}{M_{\text{raw}}(d_{\text{ref}})}$ _____
    b. Dose to water at $d_{\text{ref}} =$ _____ Gy
    c. Dose / MU at $d_{\text{ref}} =$ _____ Gy/MU [$10b/3c$]

11. Dose to water / MU at $d_{\max}$ (if relevant locally)
    a. $\%dd(d_{\text{ref}})$ as used clinically: _____
    b. Dose / MU at $d_{\max} =$ _____ Gy/MU [$10c/(11a/100)$]

# TG–51 Worksheet C: $k_{\text{ecal}}N_{D,w}^{60Co}$ for plane-parallel chambers

There are two methods for determining $k_{\text{ecal}}N_{D,w}^{60Co}$ for a plane-parallel chamber. Method A uses cross-calibration against a calibrated cylindrical chamber and is the preferred method. Method B uses a $^{60}$Co absorbed-dose calibration factor.

## Method A: Cross-Calibration

1. Site data
   - Institution: _____
   - Physicist: _____
   - Date: _____
   - Accel Mfr: _____
   - Model &serial number: _____
   - Nominal $e^-$ energy/beam identifier: _____ MeV

2. Dose using cylindrical chamber
   Do reference dosimetry for this beam using Worksheet B.
   Transfer the following information from that worksheet:
   - a. Date: _____ [B:1]
   - b. Beam quality $R_{50}$: _____ [B:4$a$]
   - c. Reference depth, $d_{\text{ref}}$: _____ [B:4$b$]
   - d. Dose / MU at $d_{\text{ref}}$: _____ [B:10$c$]
   - e. Number of MU[same used here): _____ [B:3$c$]

Now place the point of measurement of the plane-parallel chamber at $d_{\text{ref}}$

3. Temperature/Pressure Correction (Sec.VII.C)
   - a. Temperature: _____ °C
   - b. Pressure: _____ kPa [=mmHg·$\frac{101.33}{760.}$]
   - c. $P_{TP}$: _____ $\left[Eq.(10) = \left(\frac{273.2+3a}{295.2}\right)\left(\frac{101.33}{3b}\right)\right]$

4. Polarity Correction (Sec.VII.A)
   - $M_{\text{raw}}^{+}$: _____ C or rdg
   - $M_{\text{raw}}^{-}$: _____ C or rdg
   - a. $M_{\text{raw}}$ (for polarity used clinically): _____ C or rdg
   - b. $P_{\text{pol}}$: _____ $\left[Eq.(9) = \left|\frac{(M_{\text{raw}}^{+} - M_{\text{raw}}^{-})}{2M_{\text{raw}}}\right|\right]$

## Worksheet C: $k_{\text{ecal}}N_{D,w}^{^{60}Co}$ for plane-parallel chambers (cont)

5. $P_{\text{ion}}$ measurements (Sec.VII.D.2)
   Operating voltage $= V_H$: _____ V
   Lower voltage $V_L$: _____ V
   $M_{\text{raw}}^H$: _____ C or rdg
   $M_{\text{raw}}^L$: _____ C or rdg
   $P_{\text{ion}}(V_H)$ (pulsed/swept beam, Eq.(12)): _____ $\left[\left(1.-\frac{V_H}{V_L}\right)/\left(\frac{M_{\text{raw}}^H}{M_{\text{raw}}^L}-\frac{V_H}{V_L}\right)\right]$
   If $P_{\text{ion}} > 1.05$, another ion chamber should be used.

6. Corrected ion. ch. rdg. $M$ (Sec.VII)
   $$M = P_{\text{ion}}P_{TP}P_{\text{elec}}(=1.0)P_{\text{pol}}M_{\text{raw}} = [5\cdot 3c\cdot 1.0\cdot 4b\cdot 4a]$$
   Fully corrected $M$(Eq.(8)): _____ C or rdg

7. Determination of $k'_{R_{50}}$ for plane-parallel chamber, beam quality $R_{50}(2b)$
   i. $k'_{R_{50}}$ from figures _____ [Fig 6 or 8]
   or ii. $k'_{R_{50}}$ from analytic expression for well-guarded plane-parallel chambers
   $k'_{R_{50}} = 1.2239 - 0.145(R_{50})^{0.214}$ _____ [Eq.(20) $2 \le R_{50} \le 20$cm]

8. Cross-calibration value
   $\left(k_{\text{ecal}}N_{D,w}^{^{60}Co}\right)^{pp} = \frac{(D_w/MU)^{cyl}MU}{\left(Mk'_{R_{50}}\right)^{pp}} = \left[\frac{2d\cdot 2e}{6\cdot 7(i\ or\ ii)}\right]$ _____ Gy/C(or Gy/rdg)

### Method B: $^{60}$Co Calibration

1. Instrumentation
   a. Chamber model: _____
   Serial number: _____
   Waterproof: yes☐ no☐
   If no, is waterproofing $\le 1$ mm PMMA or thin latex?: yes☐ no☐
   b. Electrometer model: _____
   Serial number: _____
   i. $P_{\text{elec}}$,electrom. corr factor(Sec.VII.B): _____ C/C or C/rdg.
   c. Calibration Factor $N_{D,w}^{^{60}Co}$ (Sec.V): _____ Gy/C (or Gy/rdg)
   Date of report (not to exceed 2 years): _____
2. Determination of $k_{\text{ecal}}$
   Chamber model used to get $k_{\text{ecal}}$: _____
   a. $k_{\text{ecal}}$: _____ [Table II]
3. $k_{\text{ecal}}N_{D,w}^{^{60}Co}$: _____ Gy/C(or Gy/rdg)

# TG–51 Worksheet D: Electron Beams using Plane-Parallel Chambers

1. Site data
   - Institution: _____
   - Physicist: _____
   - Date: _____
   - Accel Mfr: _____
   - Model &serial number: _____
   - Nominal electron energy/beam identifier: _____ MeV

2. Instrumentation
   a. Chamber model: _____
   Serial number: _____
   Waterproof: yes☐ no☐
   If no, is waterproofing $\leq 1$ mm PMMA or thin latex?: yes☐ no☐

   b. Electrometer model: _____
   Serial number: _____

   i. $P_{\text{elec}}$,electrom. corr factor(Sec.VII.B): take as 1.0 if using cross-calibration.
   $P_{\text{elec}}$ : _____ C/C or C/rdg

3. Measurement Conditions (point of measurement at $d_{\text{ref}}$)
   a. Distance SSD: _____ cm
   b. Field Size on surface: _____ $\text{cm}^2$
   c. Number of monitor units: _____ MU

4. Beam Quality (Sec.VIII.C)
   Measure $I_{50}$ by measuring depth-ionization curve and, for cylindrical chambers only, shifting curve upstream by 0.5 $r_{\text{cav}}$

   $I_{50}$ _____ cm
   a.i. If $2 \leq I_{50} \leq 10$ cm:
   $R_{50} = 1.029 I_{50} - 0.06$ _____ cm
   ii. If $I_{50} > 10$ cm:
   $R_{50} = 1.059 I_{50} - 0.37$ _____ cm

   b. Reference depth $d_{\text{ref}} = 0.6 R_{50} - 0.1$ _____ cm

## Worksheet D: Electron Beams - Plane-Parallel Chambers (cont)

5. Determination of $k_{\text{ecal}}N_{D,w}^{^{60}Co}$ and $k'_{R_{50}}$ (Sec.X.C)

a. $k_{\text{ecal}}N_{D,w}^{^{60}Co}$ (Worksheet C - A:8 or B:3): _____ Gy/C (or Gy/rdg)
b. i. $k'_{R_{50}}$ from figures _____ [Fig 6 or 8]

or ii. $k'_{R_{50}}$ from analytic expression for well-guarded plane-parallel chamber

$k'_{R_{50}} = 1.2239 - 0.145(R_{50})^{0.214}$ _____ [Eq.(20) $2 \le R_{50} \le 20$cm]

6. Temperature/Pressure Correction (Sec.VII.C)

a. Temperature: _____ °C
b. Pressure: _____ kPa [=mmHg·$\frac{101.33}{760.}$]
c. $P_{TP}$: _____ $\left[Eq.(10) = \left(\frac{273.2+6a}{295.2}\right)\left(\frac{101.33}{6b}\right)\right]$

7. Polarity Correction (Sec.VII.A)

$M_{\text{raw}}^{+}$: _____ C or rdg
$M_{\text{raw}}^{-}$: _____ C or rdg
a. $M_{\text{raw}}$ (for polarity of calibration): _____ C or rdg
b. $P_{\text{pol}}$: _____ $\left[Eq.(9) = \left|\frac{(M_{\text{raw}}^{+} - M_{\text{raw}}^{-})}{2M_{\text{raw}}}\right|\right]$

8. $P_{\text{ion}}$ measurements (Sec.VII.D.2)

Operating voltage $= V_H$: _____ V
Lower voltage $V_L$: _____ V
$M_{\text{raw}}^{H}$: _____ C or rdg
$M_{\text{raw}}^{L}$: _____ C or rdg

$P_{\text{ion}}(V_H)$ (pulsed/swept beam, Eq.(12)): _____ $\left[\left(1. - \frac{V_H}{V_L}\right) \Big/ \left(\frac{M_{\text{raw}}^{H}}{M_{\text{raw}}^{L}} - \frac{V_H}{V_L}\right)\right]$

If $P_{\text{ion}} > 1.05$, another ion chamber should be used.

9. Corrected ion. ch. rdg. $M$ (Sec.VII)

$$M = P_{\text{ion}}P_{TP}P_{\text{elec}}P_{\text{pol}}M_{\text{raw}} = [8 \cdot 6c \cdot 2bi \cdot 7b \cdot 7a]$$

Fully corrected $M$(Eq.(8)): _____ C or rdg

10. Dose to water at reference depth, $d_{\text{ref}}$

$$D_w^Q = Mk'_{R_{50}}\ k_{\text{ecal}}N_{D,w}^{^{60}Co} = [9 \cdot 5b \cdot 5a\ ] \text{ Eq.(6)}$$

a. Dose to water at $d_{\text{ref}} =$ _____ Gy

b. Dose / MU at $d_{\text{ref}} =$ _____ Gy/MU $[10a/3c]$

11. Dose to water / MU at $d_{\max}$ (if relevant locally)

a. $\%dd(d_{\text{ref}})$ as used clinically: _____
b. Dose / MU at $d_{\max} =$ _____ Gy/MU $[10b/(11a/100)]$

## APPENDIX: EQUIPMENT NEEDED

To implement this protocol the following minimal set of dosimetric equipment is needed.

(i) A secondary-standard ion chamber, associated electrometer (and cables), all of high-quality. These are calibrated when first purchased, after repairs, whenever internal checks suggest problems and at least every two years. Calibrations must be traceable to the appropriate national primary standard for absorbed dose to water (Sec. V). For photon beams the chamber must be cylindrical (Secs. IV and IX B). For electron beams with energies of 6 MeV or less, plane-parallel chambers are mandatory, preferred for beams of 10 MeV or less and can be used for any energy (Sec. X).

(ii) Equipment to allow for two independent checks of the secondary-standard ion chamber (check sources, independent dosimetry systems, a $^{60}$Co unit, Sec. V).

(iii) A system which allows the voltage applied to the ion chamber to be set to at least two different voltages differing by a factor of 2 or more and which allows for reversing the applied polarity (Sec. VII).

(iv) If the ion chamber is not inherently waterproof, a PMMA waterproofing sleeve of $<1$ mm thickness or other approved waterproofing methods (Sec. V A).

(v) A water phantom (dimensions at least 30 cm on each side) which allows for the measurement of depth-dose curves (preferably with a scanning system) and allows for accurate placement of the ion chamber at a specified depth (Sec. VI).

(vi) If calibrating a beam of 10 MV or greater, a lead foil with area adequate to intercept the entire beam, with a thickness within 20% of 1 mm (Sec. VIII B).

(vii) A high-quality system for measuring the local air pressure in the room where the measurements are being made (Sec. VII C).

(viii) A high-quality system for measuring the temperature of the water near the ion chamber when doing reference dosimetry (Sec. VII C).

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