Clinical reference dosimetry: Comparison between AAPM TG-21 and TG-51 protocols

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We compare the results of absorbed dose determined at reference conditions according to the AAPM TG-21 dose calibration protocol and the new AAPM TG-51 protocol. The AAPM TG-21 protocol for absorbed dose calibration is based on ionization chambers having exposure calibration factors for ^{60}Co gamma rays, N_x. The new AAPM TG-51 dosimetry protocol for absorbed dose calibration is based on ionization chambers having ^{60}Co absorbed dose-to-water calibration factor, $N_{D,w}^{^{60}\mathrm{Co}}$. This study shows that the dose changes are within 1% for a cobalt beam, 0.5% for photon energies of 6 and 18 MV, and 2%–3% for electron beams with energies of 6 to 20 MeV. The chamber primary calibration factors, N_x and $N_{D,w}^{^{60}\mathrm{Co}}$, are traceable to the Canadian primary standards laboratory (NRCC). We also present estimated dose changes between the two protocols when calibration factors are traceable to NIST in the United States. © *2000 American Association of Physicists in Medicine.* [S0094-2405(00)00406-5]

Key words: clinical reference dosimetry, external beam calibration, TG-51 protocol, TG-21 protocol

I. INTRODUCTION

Beam calibration lies at a critical point in the overall chain in the accuracy of radiotherapy. It is very important to ensure the consistency of reference dosimetry at the level of clinical beam calibration. As the new AAPM dosimetry protocol TG-51[1] has become available, a change from TG-21 to TG-51 is recommended. The new TG-51 protocol represents a radical departure from the AAPM TG-21 protocol.[2]

Both protocols use ionization chambers to calibrate clinical photon and electron beams. The dose calibration according to the AAPM TG-21 dosimetry protocol[2] is based on using ^{60}Co exposure calibration factors, N_x, to determine N_{gas}. Spencer–Attix cavity theory is used with other data to determine the absorbed dose to water. The new AAPM TG-51 protocol[1] for clinical dosimetry is based on using ^{60}Co absorbed dose-to-water calibration factor, $N_{D,w}^{^{60}\mathrm{Co}}$. The calculated k_Q values given in TG-51 are also based on cavity theory.

In the new TG-51 protocol, beam quality for photon beams is specified by $\%\mathrm{dd}(10)_x$, the photon component of the percentage depth dose at 10 cm depth for a field size of $10\times10\,\mathrm{cm}^2$ on the surface of a phantom at an SSD of 100 cm. The beam quality for electrons is specified by R_{50}, the depth at which the absorbed dose falls to 50% of maximum dose. R_{50} is determined directly from the measured value of I_{50}, the depth at which the ionization falls to 50% of maximum value.

For photon beams, clinical reference dosimetry is performed in either an SSD or SAD setup with $10\times10\,\mathrm{cm}^2$ field size defined on the phantom surface for an SSD setup or at the depth of the detector for an SAD setup. The depth for calibration purposes is 10 cm for photon beams.

For electron beams, clinical reference dosimetry is performed with a field size of $\geqslant10\times10\,\mathrm{cm}^2$ ($20\times20\,\mathrm{cm}^2$ for $R_{50}>8.5\,\mathrm{cm}^2$) and SSD between 90 and 110 cm. The reference depth for electron beam dose calibration is changed from $d_{\max}$ in TG-21 (Ref. 2) to the new reference depth, $d_{\mathrm{ref}}=0.6R_{50}-0.1\,\mathrm{cm}$ in TG-51.[1] In TG-21, the reference depth is the maximum of the depth-ionization curve, while in TG-25 (Ref. 3) the depth is the maximum of the depth-dose curve. For lower energy electron beams the two depths are very close. In this study we treat $d_{\max}$ as the depth of maximum dose.

It is important to evaluate the changes in clinical reference dosimetry after the implementation of the TG-51 protocol. This study presents the results of differences in reference absorbed dose determined using the AAPM TG-21 and TG-51 protocols for high-energy photon (^{60}Co, 6 and 18 MV) and electron (6–20 MeV) beams. It is expected that there will be variations in dose changes among countries even when their primary standards for absorbed dose or air kerma remain unchanged, if the ratio of calibration factors based on their primary standards for absorbed dose and air kerma differ. It is shown in a study by Shortt *et al.*[4] that differences of 1.1% exist in this ratio between the U.S. and Canada.

II. METHODS AND MATERIALS

A. Reference dose according to the AAPM TG-21 protocol

According to the TG-21 protocol,[2] the dose to water, D_w^Q, is given by

$$D_w^{\mathrm{TG-21}} = \overline{M} N_{\mathrm{gas}} \left(\frac{\overline{L}}{\rho}\right)_a^w P_{\mathrm{ion}} P_{\mathrm{repl}} P_{\mathrm{wall}}, \quad (1)$$

where $\overline{M} = M_{\mathrm{raw}} P_{TP} P_{\mathrm{pol}} P_{\mathrm{elec}}$ is the temperature- and pressure-corrected electrometer reading which also includes the polarity effect and the electrometer correction factor when the electrometer and ion chamber are calibrated separately. When the electrometer and ion chamber are calibrated separately, the AAPM TG-21 does not give any recommendation with regard to the electrometer's calibration factor P_{elec}. In Canada, an electrometer and ion chamber are calibrated together; therefore, the values of $\overline{M}$ includes the electrometer's calibration factor. In this study we assume that $\overline{M}$ includes the electrometer's calibration factor, even when the electrometer and the ion chamber are calibrated separately. N_{gas} is the cavity-gas calibration factor, $(\overline{L}/\rho)_a^w$ is the ratio of the mean, restricted collision mass stopping power of water to air, P_{ion} is a factor that corrects for ionization recombination losses that occur at the time of calibration of the user's radiation therapy beam, P_{wall} is a wall correction which accounts for the fact that the wall and other parts of the chamber are not made of the same material as the medium, P_{repl} is a replacement correction factor which depends upon the type and energy of the radiation and the gradient of the depth-dose curve at the point of measurement. P_{repl} can be thought of as having two components, the gradient and fluence correction factors:[5] $P_{\mathrm{repl}} = P_{\mathrm{gr}} P_{\mathrm{fl}}$, where P_{gr} becomes unity at $d_{\max}$. The cavity-gas calibration factor, N_{gas}, is calculated from the ^{60}Co exposure calibration factor, N_x, according to the TG-21 protocol[2]

$$N_{\mathrm{gas}} = N_x \frac{k(W/e) A_{\mathrm{ion}} A_{\mathrm{wall}} \beta_{\mathrm{wall}}}{\alpha \left(\frac{\overline{L}}{\rho}\right)_{\mathrm{gas}}^{\mathrm{wall}} \left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{wall}}^{\mathrm{air}} + (1-\alpha) \left(\frac{\overline{L}}{\rho}\right)_{\mathrm{gas}}^{\mathrm{cap}} \left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{cap}}^{\mathrm{air}}}, \quad (2)$$

where A_{ion} is ion-collection efficiency obtained from primary laboratory, $k = 2.58 \times 10^{-4}$ C/kg/R, $W/e = 33.7$ J/C, $\beta_{\mathrm{wall}} = 1.005$, A_{wall} is a wall-correction factor. In our case, the value of A_{ion} is 0.2% less than unity, which is within the uncertainties of measurements.

B. Reference dose according to the AAPM TG-51 protocol

According to TG-51,[1] the absorbed dose to water, D_w^Q, for a given number of monitor units (or minutes for ^{60}Co) from a radiation of quality Q

$$D_w^Q = M k_Q N_{D,w}^{^{60}\mathrm{Co}}, \quad (3)$$

where $M = M_{\mathrm{raw}} P_{\mathrm{ion}} P_{TP} P_{\mathrm{elec}} P_{\mathrm{pol}}$, P_{elec} takes into account the electrometer's calibration factor if the electrometer and ion chamber are calibrated separately, P_{pol} corrects for any polarity effects; k_Q is the quality conversion factor, a chamber-specific 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); $N_{D,w}^{^{60}\mathrm{Co}}$ is the absorbed dose-to-water calibration factor which should be traceable to primary standards laboratory. The AAPM TG-51 provides calculated values of k_Q for various ionization chambers.

C. Comparison of determined absorbed dose to water between two protocols

In this study, the comparison is done by calculating the ratio of determined absorbed dose to water according to the TG-51 compared to that according to TG-21 protocol.

1. Photon beams

For photon beams, the gradient effects are included implicitly in the correction factor k_Q in the TG-51 protocol.[1] The ratio of absorbed dose to water at the reference point can be written as

$$\frac{D_w^{\mathrm{TG-51}}(Q)}{D_w^{\mathrm{TG-21}}(Q)} = \frac{k_Q}{(\overline{L}/\rho)_a^w P_{\mathrm{repl}} P_{\mathrm{wall}}} \cdot \frac{N_{D,w}^{^{60}\mathrm{Co}}}{N_{\mathrm{gas}}}. \quad (4)$$

Here, we use reference depth at 10 cm although the reference depth recommended by TG-21 for photon beams is at 5 or 7 cm depth depending on the energy. In practice it makes no difference. All parameters on the right side of Eq. (4) can be obtained from the TG-21 and the TG-51 protocols based on the two different beam quality specifiers [TPR_{10}^{20} and $\%\mathrm{dd}(10)_x$]. The chamber primary calibration factors $N_{D,w}^{^{60}\mathrm{Co}}$ and N_x [N_{gas} related to N_x through Eq. (2)] are provided by the standards laboratory.

2. Electron beams

For electron beams in TG-51, $k_Q = P_{\mathrm{gr}}^Q k'_{R_{50}} k_{\mathrm{ecal}}$, where P_{gr}^Q is the gradient correction factor which is dependent on the ionization gradient at the point of measurement, k_{ecal} is needed to convert $N_{D,w}^{^{60}\mathrm{Co}}$ into an electron beam absorbed dose-to-water calibration factor $N_{D,w}^{Q_{\mathrm{ecal}}}$ for a selected beam quality Q_{ecal}, and $k'_{R_{50}}$ is needed to convert $N_{D,w}^{Q_{\mathrm{ecal}}}$ into $N_{D,w}^Q$ for any beam quality Q. According to the TG-51 protocol,[1] clinical reference dosimetry for electron beams is performed at a depth of $d_{\mathrm{ref}} = 0.6R_{50} - 0.1$[cm], while according to the TG-21 protocol[2] clinical reference dosimetry for electron beams is performed at a depth of $d_{\max}$. In order to compare the dose at $d_{\max}$ based on the two protocols, one has to use clinical percentage depth-dose data for a given beam to determine the dose at $d_{\max}$ from that at d_{ref}. The ratio of doses at $d_{\max}$ can be written as

$$\frac{D_w^{\mathrm{TG-51}}(Q,d_{\max})}{D_w^{\mathrm{TG-21}}(Q,d_{\max})}=\frac{D_w^{\mathrm{TG-51}}(Q,d_{\mathrm{ref}})/\%\mathrm{dd}(d_{\mathrm{ref}})}{D_w^{\mathrm{TG-21}}(Q,d_{\max})}=\frac{M(Q,d_{\mathrm{ref}})P_{\mathrm{gr}}^{Q}k'_{R_{50}}(Q)k_{\mathrm{ecal}}N_{D,w}^{^{60}\mathrm{Co}}/\%\mathrm{dd}(d_{\mathrm{ref}})}{\overline{M}(Q,d_{\max})P_{\mathrm{ion}}(\overline{L}/\rho)_a^w(Q,d_{\max},\mathrm{TG\text{-}21})P_{\mathrm{repl}}(Q,d_{\max})N_{\mathrm{gas}}}. \tag{5}$$

When ionization chambers are used to determine the percentage depth-dose curve, the procedures require stopping power ratios. In the TG-51 protocol, the water-to-air stopping-power ratios for realistic electron beams have been used and these differ from the monoenergetic stopping-power ratios used in TG-21. TG-51 recommends that the expression presented by Burns *et al.*[6] for stopping-power ratios in realistic electron beams as a function of R_{50} and depth, be used to determine the clinical depth-dose data [see Eq. (11) below]. Other methods of measuring the depth-dose curve, such as with film, diodes, and TLDs may be more convenient than ionization chamber measurements. However, these measurements should be compared to the data obtained with ionization chambers in water as recommended in TG-25 (Ref. 3).

To use Eq. (5) to determine the dose differences between the two protocols, one also needs the values of factors P_{gr}^{Q}, $k'_{R_{50}}$, and k_{ecal}. The values of $k'_{R_{50}}$ and k_{ecal} are provided for various ionization chambers in TG-51. The gradient correction factor, P_{gr}^{Q}, is not necessary for plane-parallel chambers. For cylindrical chambers, it is determined as[1]

$$P_{\mathrm{gr}}^{Q}=\frac{M_{\mathrm{raw}}(d_{\mathrm{ref}}+0.5r_{\mathrm{cav}})}{M_{\mathrm{raw}}(d_{\mathrm{ref}})}, \tag{6}$$

where r_{cav} is the radius of the chamber's cavity in cm; the ratio in the equation is the ratio of the integrated charges or ionization current with the central axis of the chamber at $d_{\mathrm{ref}}+0.5r_{\mathrm{cav}}$ and d_{ref}.

It should be noted that TG-51 recommends that plane-parallel chambers be used for beams with incident energies of 6 MeV or less.

For electron beam dosimetry, AAPM TG-51 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 some plane-parallel chambers appear to be very sensitive to small features of their construction, it is recommended that, when possible, plane-parallel chambers be calibrated against calibrated cylindrical chambers in a high-energy electron beam. The product of $k_{\mathrm{ecal}}N_{D,w}^{^{60}\mathrm{Co}}$ is determined for the plane-parallel chambers as[1]

$$[k_{\mathrm{ecal}}N_{D,w}^{^{60}\mathrm{Co}}]^{\mathrm{pp}}=\frac{[MP_{\mathrm{gr}}^{Q_c}k'_{R_{50}}(Q_c)k_{\mathrm{ecal}}N_{D,w}^{^{60}\mathrm{Co}}]^{\mathrm{cyl}}}{[Mk'_{R_{50}}(Q_c)]^{\mathrm{pp}}}, \tag{7}$$

where the point of measurement of both the calibrated cylindrical chamber and the plane-parallel chamber is at d_{ref}. In Eq. (7) we have introduced an electron beam quality index used in the cross calibration as Q_c.

Values of N_{gas} for plane-parallel chambers are determined by Eq. (8), as recommended in the TG-21,[2,7] using the highest electron beam energy available and a cylindrical chamber for which N_{gas} is known.

$$N_{\mathrm{gas}}^{\mathrm{pp}}=\frac{[\overline{M}N_{\mathrm{gas}}P_{\mathrm{ion}}P_{\mathrm{gr}}P_{\mathrm{fl}}]^{\mathrm{cyl}}}{[\overline{M}P_{\mathrm{ion}}]^{\mathrm{pp}}}. \tag{8}$$

The location of the point of measurement is taken as the center of the cylindrical chamber and the inner surface of the entrance wall of the plane-parallel chamber. The point of measurement for each chamber is placed at $d_{\max}$. The value of P_{gr} is unity at $d_{\max}$.

After the product of $k_{\mathrm{ecal}}N_{D,w}^{^{60}\mathrm{Co}}$ and values of N_{gas} are determined for the plane-parallel chamber, Eq. (5) can be used to determine the dose changes between the two protocols when plane-parallel chambers are used for electron beam absorbed dose calibration.

3. Calculational approach for electron beams

In this section, we present a calculational approach for electron beams in order to reduce experimental calibration setup uncertainties.

If the value of %dd is to be obtained by using an ionization chamber, $\%\mathrm{dd}(d_{\mathrm{ref}})$ can be written as

$$\%\mathrm{dd}(d_{\mathrm{ref}})=\frac{M(Q,d_{\mathrm{ref}})\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\mathrm{ref}},\ \text{Eq. (10)})P_{\mathrm{repl}}(Q,d_{\mathrm{ref}})}{M(Q,d_{\max})\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\max},\ \text{Eq. (11)})P_{\mathrm{repl}}(Q,d_{\max})}, \tag{9}$$

where stopping-power ratios of realistic electron beams are given by Eqs. (10) and (11) (Ref. 6) as recommended by the AAPM TG-51 protocol.

$$\left(\frac{\overline{L}}{\rho}\right)_a^w(R_{50},d_{\mathrm{ref}})=a_1+b_1(R_{50})^{c_1}, \tag{10}$$

where the values are $a_1=1.2534$ $b_1=-0.1487$, and $c_1=0.2144$.

$$\left(\frac{\overline{L}}{\rho}\right)_a^w(R_{50},z)=\frac{a+b(\ln R_{50})+c(\ln R_{50})^2+d(z/R_{50})}{1+e(\ln R_{50})+f(\ln R_{50})^2+g(\ln R_{50})^3+h(z/R_{50})}, \tag{11}$$

where the values for the eight coefficients are: $a=1.0752$, $b=-0.508\,67$, $c=0.088\,670$, $d=-0.084\,02$, $e=-0.428\,06$, $f=0.064\,627$, $g=0.003\,085$, and $h=-0.124\,60$.

By inserting Eq. (9) into Eq. (5) and expanding M and $\overline{M}$, writing $P_{\text{repl}}=P_{\text{gr}}P_{\text{fl}}$ and recalling that $P_{\text{gr}}=1.00$ at $d_{\max}$, we have

$$\frac{D_w^{\text{TG-51}}(Q,d_{\max})}{D_w^{\text{TG-21}}(Q,d_{\max})}=\frac{\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\max},\ \text{Eq. (11)})}{\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\max},\text{TG-21})}\times\frac{k'_{R_{50}}(Q)}{\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\text{ref}},\ \text{Eq. (10)})P_{\text{fl}}(Q,d_{\text{ref}})}\times\frac{k_{\text{ecal}}N_{D,w}^{^{60}\text{Co}}}{N_{\text{gas}}}. \tag{12}$$

If a cylindrical chamber is used in the electron beam calibration, Eq. (12) can be used to calculate the dose changes between two protocols, since parameters on the right side of the equation are available from TG-21 and TG-51 protocols and Eqs. (10) and (11), except the values of P_{fl} which will be discussed below. The absorbed dose-to-water calibration factor $N_{D,w}^{^{60}\text{Co}}$ and the exposure calibration factor N_x [N_{gas} related to N_x through Eq. (2)] for the chamber are provided by the standards laboratory. In using Eq. (12) one needs the fluence correction factors P_{fl}, at d_{ref}, away from $d_{\max}$, the point at which most previous measurements were done.[7–9] These factors have been parametrized in terms of $\overline{E}_z=\overline{E}_o(1-z/R_p)$, the mean energy at the point of measurement. It is assumed that the measured values apply, despite no longer being at $d_{\max}$. Rogers[10] has recast the data so that the value of P_{fl} at d_{ref} is given as a function of R_{50} through $R_p=1.271R_{50}-0.23\,\text{cm}$ and the cavity radius. An approximate value of $\overline{E}_o$ is given by $2.33R_{50}$. In this study we use values given by Rogers.[10] Recent measurements[11–13] indicate good agreement with this assumption for cylindrical chambers and plane-parallel chambers in electron beams with initial energies from 5 to 20 MeV. It should be noted that TG-51 uses the same P_{fl} as TG-21 since the values of P_{fl} are obtained from same measurements.[7–9]

If a plane-parallel chamber is used, the TG-51 protocol recommends that plane-parallel chambers be calibrated against calibrated cylindrical chambers in a high-energy electron beam. The product of $k_{\text{ecal}}N_{D,w}^{^{60}\text{Co}}$ is determined by using Eq. (7) for the plane-parallel chamber.[1] In order to do a comparison based solely on calculations and simplify the formula, we determine N_{gas} for plane-parallel chambers when the point of measurement is placed at d_{ref} instead of at $d_{\max}$. Equation (8) can be rewritten as

$$N_{\text{gas}}^{\text{pp}}=\frac{[\overline{M}P_{\text{gr}}^{Q_c}N_{\text{gas}}P_{\text{ion}}P_{\text{fl}}(Q_c,d_{\text{ref}})]^{\text{cyl}}}{[\overline{M}P_{\text{ion}}]^{\text{pp}}}, \tag{13}$$

where $P_{\text{gr}}^{Q_c}$ is defined in Eq. (6). In using Eq. (13), the point of measurement of both the calibrated cylindrical chamber and the plane-parallel chamber is at d_{ref}. By inserting Eq. (7) and (13) into Eq. (12), we have

$$\frac{D_w^{\text{TG-51}}(Q,d_{\max})}{D_w^{\text{TG-21}}(Q,d_{\max})}=\frac{\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\max},\ \text{Eq. (11)})}{\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\max},\text{TG-21})}\times\frac{[k'_{R_{50}}(Q)]^{\text{pp}}}{\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\text{ref}},\text{Eq. (10)})[P_{\text{fl}}(Q,d_{\text{ref}})]^{\text{pp}}}\times\frac{[k'_{R_{50}}(Q_C)k_{\text{ecal}}]^{\text{cyl}}}{[k'_{R_{50}}(Q_C)]^{\text{pp}}[P_{\text{fl}}(Q_C,d_{\text{ref}})]^{\text{cyl}}}\times\left[\frac{N_{D,w}^{^{60}\text{Co}}}{N_{\text{gas}}}\right]^{\text{cyl}}, \tag{14}$$

where Q_C is the electron beam quality used in the cross calibration. If the beam quality Q_C is taken as $R_{50}=7.5\,\text{cm}$, which is the same beam quality as Q_{ecal} in the TG-51 protocol, the value of $k'_{R_{50}}(Q_C)$ becomes unity[10] and Eq. (14) can be further simplified to

$$\frac{D_w^{\text{TG-51}}(Q,d_{\max})}{D_w^{\text{TG-21}}(Q,d_{\max})}=\frac{\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\max},\ \text{Eq. (11)})}{\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\max},\text{TG-21})}\times\frac{[k'_{R_{50}}(Q)]^{\text{pp}}}{\left(\frac{\overline{L}}{\rho}\right)_a^w(Q,d_{\text{ref}},\text{Eq. (10)})[P_{\text{fl}}(Q,d_{\text{ref}})]^{\text{pp}}}\times\frac{[k_{\text{ecal}}]^{\text{cyl}}}{[P_{\text{fl}}(Q_{\text{ecal}},d_{\text{ref}})]^{\text{cyl}}}\left[\frac{N_{D,w}^{^{60}\text{Co}}}{N_{\text{gas}}}\right]. \tag{15}$$

Equation (15) can be used to calculate the dose differences between the two protocols when a plane-parallel chamber is used and a cylindrical chamber for which the calibration factors, $N_{D,w}^{^{60}\text{Co}}$ and N_x, are traceable to a primary calibration laboratory.

TABLE I. Five ionization chamber calibration factors used in this study. The calibration factors of N_x and $N_{D,w}^{^{60}Co}$ are traceable to Canadian standards laboratory (NRCC).

Chamber	Model	Type	N_x (R/div)	N_{gas} (cGy/div)	$N_{D,w}^{^{60}Co}$ (cGy/div)
Farmer-like	PR-06C	···	1.017	0.863	0.973
Farmer-like	NE2571	···	1.022	0.873	0.981
Plane-parallel	NACP(#1)	02	···	2.78	···
Plane-parallel	NACP(#2)	02	···	2.71	3.20
Plane-parallel	Markus	W23343	···	9.68	···

D. Incident beams and detectors

The ^{60}Co beam is from an AECL T780C unit. The photon beams of energies 6 and 18 MV and the electron beams of energies from 6 to 20 MeV are from ELEKTA SL20 and Siemens KD2 linear accelerators.

For photon beams the beam quality conversion factor, k_Q, for a chamber can be obtained from tables or figures in TG-51 for given values of $\%\mathrm{dd}(10)_x$. For energies $\geqslant$ 10 MV, the values of $\%\mathrm{dd}(10)_x$ (excluding electron contamination) are calculated from the values of $\%\mathrm{dd}(10)_{Pb}$ (including electron contamination). According to the TG-51 protocol, a 1 mm lead foil is used to measure $\%\mathrm{dd}(10)_{Pb}$ for a $10\times10\,\mathrm{cm}^2$ field at the phantom surface at SSD=100 cm. The lead foil was placed in the path of the beam at 30 and 50 cm from the surface of the water phantom for an 18 MV beam from ELEKTA SL20 and an 18 MV beam from Siemens KD2, respectively. The design of the ELEKTA machine makes it difficult to place the lead foil at 50 cm from the phantom surface.

The reference dosimetry for photon beams is performed in an open beam with an SAD setup at depth of 10 cm in a water tank and the field size $10\times10\,\mathrm{cm}^2$ at SAD=100 cm for both protocols. The chamber waterproof sleeve is made of polymethylmethacrylate (PMMA)$\leqslant$1 mm thick.

The two cylindrical chambers used in this study are a PR-06C and an NE2571. Both cylindrical chamber calibration factors ($N_{D,w}^{^{60}Co}$ and N_x) were provided by the Canadian primary standards laboratory (NRCC). The three plane-parallel chambers are two NACP chambers made by Scanditronix and one Markus chamber. The calibration factor, $N_{D,w}^{^{60}Co}$, for only one plane-parallel chamber, NACP (#2), was traceable to NRC of Canada. Chamber calibration factors are listed in Table I.

E. Estimated uncertainties

For photon beams, the uncertainties in the ratio of absorbed doses [Eq. (4)] come from procedures in following the protocols to determine the various parameters, such as k_Q, P_{repl}, P_{wall}, $(\overline{L}/\rho)_a^w$, and the cavity-gas calibration factor N_{gas}. For examples, the uncertainty in the measured values of $\%\mathrm{dd}(10)_x$ can contribute to the uncertainty in the determined value of k_Q; the uncertainty in the measured TPR_{10}^{20} can contribute to the uncertainty in the derived values of stopping power ratio $(\overline{L}/\rho)_a^w$; the uncertainty from N_x to N_{gas}, etc. Fortunately, the actual measurement setup and measurement reading uncertainties cancel out because the reference point is the same for both protocols. Therefore, there are no measurement readings in Eq. (4).

For electron beams the reference depth in TG-21 is different from the reference depth in TG-51. The actual calibration measurement setup and measurement reading uncertainties also contribute to the uncertainties in the ratio of absorbed dose [Eq. (5)], in addition to those discussed above for photon beams. However, in the calculational approach the experiment setup and measurement reading uncertainties are avoided with compromised simplicity [see Eqs. (12) and (15)]. All uncertainties are estimated to be 1 standard deviation (68% confidence limit).

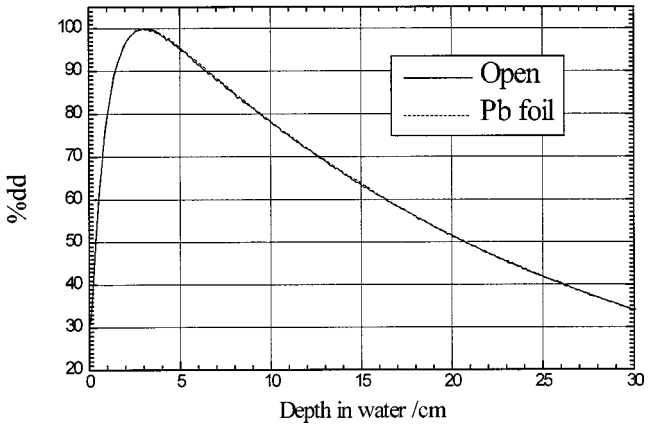

FIG. 1. Percentage depth dose curves for an 18 MV photon beams from an ELEKTA SL20 accelerator. The solid line is for open beam and the dashed line is for the beam with a 1 mm lead foil placed at 30 cm above the water surface. The $\%\mathrm{dd}(10)_x=79.6\%$ is calculated from $\%\mathrm{dd}(10)_{Pb}=78.2\%$. The detector is an IC-10 chamber ($r_{cav}=3$ mm) and the curves have been shifted upstream by $0.6r_{cav}$ according to the TG-51 protocol.

III. RESULTS

A. Photon beams

Figure 1 shows measured percentage depth-dose curves for an 18 MV photon beam from an ELEKTA SL20 linear accelerator. Very similar measured percentage depth-dose

TABLE II. Photon beam parameters used in this study. The uncertainties of measured TPR_{10}^{20} and %dd(10) are about 0.5%.

Beam	TPR_{10}^{20}	%dd(10)	$\%\mathrm{dd}(10)_{Pb}$	$\%\mathrm{dd}(10)_x$	k_Q (PR-06C)	k_Q (NE2571)
T780C, ^{60}Co	0.571	59.0	···	59.0	1.000	1.000
SL20, 6 MV	0.681	67.5	···	67.5	0.992	0.993
KD2, 6 MV	0.674	68.0	···	68.0	0.991	0.992
SL20, 18 MV	0.778	78.2	78.2	79.6	0.971	0.974
KD2, 18 MV	0.771	78.1	78.2	78.8	0.972	0.976

TABLE III. Dose changes $D^{\text{TG-51}}/D^{\text{TG-21}}$ at 10 cm depth for cobalt-60, 6 and 18 MV photon beams based on calibrations traceable to NRC of Canada or NIST. Data are obtained by using Eq. (4). The uncertainty for the results of the dose comparison is estimated to be about 1%. Values when calibrations factors are traceable to NIST in the U.S. are based on a study by Shortt *et al.* (Ref. 4).

		ELEKTA SL20		Siemens KD2		T780C
	Chamber	6 MV	18 MV	6 MV	18 MV	^{60}C
NRCC	PR-06C	1.002	1.000	1.001	0.997	1.011
	NE2571	0.998	1.004	0.997	0.999	1.003
NIST	PR-06C	1.013	1.011	1.012	1.008	1.022
	NE2571	1.009	1.015	1.008	1.010	1.014

curves for a Siemens KD2 linear accelerator are not shown. It can be seen that there is virtually no change in the depth-dose curve for open and open plus lead foil incident beams.

Tables I and II list the chamber calibration factors and photon beam data. Values of N_{gas} for cylindrical chambers are calculated with Eq. (2) according to the TG-21 protocol. For plane-parallel chambers the values of N_{gas} are measured by using Eq. (8) according to the TG-21 protocol. The uncertainties in measured values of N_{gas} for plane-parallel chambers are estimated to be about 1%.

Table III shows the absorbed dose changes between the two protocols obtained by using Eq. (4) for cobalt, 6 and 18 MV photon beams. The chamber calibration factors are traceable to NRCC in Canada. It also presents estimated absorbed dose changes between the TG-51 and TG-21 protocols when chamber calibration factors are traceable to NIST in the U.S. This estimation is based on the study by Shortt *et al.*,[4] who showed a difference of 1.1% exists in the ratio of primary standards for absorbed dose and air kerma between the U.S. and Canada, and this ratio occurs in all equations in the comparison for the remainder of the paper.

B. Electron beams

For electron beams, we have compared the two protocols using two approaches. One is a direct measurement approach according to the protocols. The other is to use a calculational approach.

1. Results from experimental approaches

Table IV presents the results by using Eq. (5), in which the values of $\%\text{dd}(d_{\text{ref}})$ were obtained from a percentage depth-dose curve measured with a Scanditronix electron beam diode. We have used an NACP chamber measurement by using Eq. (9) to confirm the results from diode measurements. The NACP is a well-guarded plane-parallel chamber[1–3] which requires no corrections for variations in P_{repl}. The maximum deviations in the values of $\%\text{dd}(d_{\text{ref}})$ between two methods was 0.3%, which is within expected measurement uncertainties. This is performed to follow the AAPM recommendations as discussed in Sec. II C 2 on how to determine the percentage depth-dose curve for an electron beam. Measurements were done for a field size of 20 $\times 20\,\text{cm}^2$ and SSD=100 cm. The values of N_{gas} are determined for the plane-parallel chamber by using Eq. (8) against the cylindrical chamber (NE2571) in a 20 MeV elec-

TABLE IV. Results of dose comparison between two protocols determined by using the experimental approach [Eq. (5)] where values of $\%\text{dd}(d_{\text{ref}})$ were obtained from a percentage depth-dose curve measured with a diode. The electron beams are from a Siemens KD2 linear accelerator. The parallel-plane chamber used for the calibration is NACP (#2). The uncertainty for the results of dose comparison is estimated at about 1.5%. The results of the comparison are based on calibrations traceable to NRC of Canada. Similarly, when chamber calibration factors are traceable to NIST the dose changes between two protocols shown here are estimated due to the differences in the primary standards for absorbed dose and air kerma between the U.S. and Canada based on the study by Shortt *et al.* (Ref. 4).

	$\frac{D(d_{\max})^{\text{TG-51}\ a}}{D(d_{\max})^{\text{TG-21}}}$		$\frac{D(d_{\max})^{\text{TG-51}\ b}}{D(d_{\max})^{\text{TG-21}}}$		$\frac{D(d_{\max})^{\text{TG-51}\ c}}{D(d_{\max})^{\text{TG-21}}}$	
Electron beam energy (MeV)	$N_{D,w}^{^{60}\text{Co}}$ and N_x are traceable to NRCC in Canada	When $N_{D,w}^{^{60}\text{Co}}$ and N_x are traceable to NIST in US	$N_{D,w}^{^{60}\text{Co}}$ and N_x are traceable to NRCC in Canada	When $N_{D,w}^{^{60}\text{Co}}$ and N_x are traceable to NIST in US	$N_{D,w}^{^{60}\text{Co}}$ and N_x are traceable to NRCC in Canada	When $N_{D,w}^{^{60}\text{Co}}$ and N_x are traceable to NIST in US
6	1.013	1.024	1.002	1.013	0.998	1.009
9	1.020	1.031	1.009	1.020	1.005	1.016
11	1.021	1.032	1.010	1.021	1.005	1.016
13	1.023	1.034	1.012	1.033	1.008	1.019
17	1.038	1.049	1.027	1.038	1.022	1.033
20	1.033	1.044	1.022	1.033	1.017	1.028

[a]Using $N_{D,w}^{^{60}\text{Co}}$ which was traceable to primary standards laboratory for the NACP (#2) chamber and $k_{\text{ecal}}=0.888$ from the TG-51.

[b]Using $N_{D,w}^{^{60}\text{Co}}$ which was traceable to standards laboratory for the NACP (#2) chamber and $k_{\text{ecal}}=0.903/P_{\text{wall}}^{^{60}\text{Co}}=0.878$ from our previously measured value P_{wall} in a ^{60}Co beam (Ref. 12).

[c]Using the TG-51 recommended cross calibration of the NACP chamber against a cylindrical chamber (NE2571) for which the value of $N_{D,w}^{^{60}\text{Co}}$ was traceable to standards laboratory [Eq. (8)].

TABLE V. Electron beam parameters and results of comparison between two protocols using the calculational approach [Eq. (15)]. The clinical beams are from a Siemens KD2 linear accelerator. The chambers used are NACP with the NE2571 chamber. The uncertainty for the results of dose comparison is estimated to be about 1.2%. The results of the comparison are based on calibration factors traceable to NRC of Canada. Similarly, when $N_{D,w}^{^{60}\mathrm{Co}}$ and N_x are traceable to NIST in the US, the dose changes between two protocols will be 1.1% higher than reported here based on the study by Shortt *et al.* (Ref. 4).

Energy (MeV)	$d_{\max}$ (cm)	d_{ref} (cm)	R_{50} (cm)	$(\overline{L}/\rho)_a^w(d_{\max})$ TG-21	$(\overline{L}/\rho)_a^w(d_{\max})$ Eq. (11)	$(\overline{L}/\rho)_a^w(d_{\mathrm{ref}})$ Eq. (10)	$k'_{R_{50}}$ (NACP)	$\frac{D(d_{\max})^{\mathrm{TG\text{-}51}}}{D(d_{\max})^{\mathrm{TG\text{-}21}}}$ (calculated) NACP
6	1.45	1.35	2.41	1.085	1.075	1.0738	1.049	1.004
9	2.1	2.09	3.65	1.061	1.0568	1.0571	1.033	1.009
11	2.6	2.61	4.51	1.051	1.0481	1.0480	1.024	1.011
13	2.9	2.99	5.15	1.041	1.0408	1.0421	1.017	1.012
17	2.3	4.11	7.02	0.995	0.9997	1.0276	1.004	1.015
20	1.9	4.71	8.02	0.979	0.9829	1.0210	0.998	1.018

tron beam from a KD2 linear accelerator. The ionization signals were measured with the NACP#2 chamber. Dose determination at d_{ref} were performed using three different methods:

(a) Using $N_{D,w}^{^{60}\mathrm{Co}}$ which was provided by the Canadian standards laboratory (NRCC) for the NACP chamber and $k_{\mathrm{ecal}}=0.888$ from the TG-51 protocol. However, we believe that there may be a typo in the TG-51 because the values of k_{ecal} are determined by using a calculated value of P_{wall} in a ^{60}Co beam by Rogers.[10] The correct value should be $k_{\mathrm{ecal}}(=0.903/P_{\mathrm{wall}}^{^{60}\mathrm{Co}})=0.887$ for the NACP chamber.

(b) Using $N_{D,w}^{^{60}\mathrm{Co}}$ which was provided by NRCC for the NACP chamber and $k_{\mathrm{ecal}}(=0.903/P_{\mathrm{wall}}^{^{60}\mathrm{Co}})=0.878$ from our previous[12] measured value of P_{wall} in a ^{60}Co beam for this particular NACP (#2) chamber.

(c) Using the TG-51 recommended cross calibration of the NACP chamber against a cylindrical chamber (NE2571) for which the value of $N_{D,w}^{^{60}\mathrm{Co}}$ was provided by NRCC [Eq. (7)].

It should be noted that only methods (a) and (c) are according to the recommendations of TG-51 protocol in the determination of absorbed dose to water. Strictly speaking, method (b) does not follow the recommendations of TG-51 because we have used our previous measured value of P_{wall}, which is different from the recommendations. The results in Table IV contain the experimental uncertainties which are estimated to be about 1.5% by following the analysis given by Almond *et al.*[14]

Table IV also shows estimated dose changes between two protocols when chamber calibration factors are traceable to NIST in the U.S. These estimates are based on the study by Shortt.[4]

2. Results from calculational approaches

Tables V and VI show electron beam data for the KD2 and the SL20 linear accelerators, respectively. Results for the plane-parallel chamber NACP shown in Table V are obtained by using Eq. (15) with the NE2571 for which the calibration factors are given in Table I. It can be seen that corresponding results between experimental and the calcula-

TABLE VI. Electron beams parameters and results of comparison between two protocols using the calculational approach [Eq. (15)]. Chambers used are NACP and Markus chambers with the PR-06C chamber. The last column is obtained by using the calculational Eq. (12) for the PR-06C chamber. The clinical beams are from an ELEKTA SL20 linear accelerator. The uncertainty for the results of dose comparison is estimated to be about 1.2%. The results of the comparison are based on calibration factors traceable to NRC of Canada. When $N_{D,w}^{^{60}\mathrm{Co}}$ and N_x are traceable to NIST in the US, the dose changes between two protocols will be 1.1% higher than reported here based on the study by Shortt *et al.* (Ref. 4).

Beam (MV)	$d_{\max}$ (cm)	d_{ref} (cm)	R_{50} (cm)	$(\overline{L}/\rho)_a^w(d_{\max})$ TG-21	$(\overline{L}/\rho)_a^w(d_{\max})$ Eq. (11)	$\frac{D(d_{\max})^{\mathrm{TG\text{-}51}}}{D(d_{\max})^{\mathrm{TG\text{-}21}}}$ NACP	$\frac{D(d_{\max})^{\mathrm{TG\text{-}51}}}{D(d_{\max})^{\mathrm{TG\text{-}21}}}$ Markus	$\frac{D(d_{\max})^{\mathrm{TG\text{-}51}}}{D(d_{\max})^{\mathrm{TG\text{-}21}}}$ PR-06C
6	1.4	1.46	2.6	1.072	1.065	1.006	1.006	⋯
8	1.8	1.94	3.4	1.059	1.055	1.010	1.010	1.012
10	2.3	2.42	4.2	1.050	1.048	1.011	1.012	1.014
12	2.6	2.90	5.0	1.034	1.037	1.017	1.018	1.019
15	2.7	3.68	6.3	1.012	1.016	1.017	1.019	1.017
18	3.0	4.22	7.2	1.004	1.008	1.017	1.018	1.018
20	2.2	4.70	8.0	0.983	0.987	1.017	1.018	1.017

tional approaches are very similar, as shown in the second to the last column in Table IV and the last column in Table V.

Results for the cylindrical chamber (PR-06C) shown in Table VI are obtained by using Eq. (12). For the NACP chamber the value of P_{fl} is taken as unity.[2]

IV. DISCUSSION

The new TG-51 protocol is easier to apply as it avoids use of large tables of stopping-power ratios and mass-energy absorption coefficients. Although the value of the primary absorbed dose-to-water calibration factors $N_{D,w}^{^{60}\mathrm{Co}}$ has similar uncertainty to that of the primary exposure calibration factors N_x, the increase in accuracy in the clinical reference dosimetry using an absorbed dose-to-water calibrated ionization chamber instead of an exposure calibrated one arises because of following: (1) there is no extra step of calculating N_{gas} from N_x; (2) it takes into account the improvements in radiation dosimetry since TG-21 protocol was published; (3) it allows incorporation of future development of primary standards for absorbed dose in accelerator beams.

Currently the values of factors k_Q in TG-51 have been calculated using cavity theory for various cylindrical ionization chambers for reference dosimetry. For photon beams, in theory there should be little change in reference dosimetry between TG-51 and TG-21 plus other proposed changes[15,16] if the ratio of calculated $N_{D,w}^{^{60}\mathrm{Co}}/N_k$ agrees with that of primary laboratory measured $N_{D,w}^{^{60}\mathrm{Co}}/N_k$ because the discrepancies between TG-21 protocol as written in 1983 and fully corrected TG-21 protocol (i.e., based on the new understanding that is consistent with the calculations used by TG-51) are about 0.5%. According to the study by Shortt *et al.*,[4] the experimentally determined ratio, $N_{D,w}^{^{60}\mathrm{Co}}/N_k$, for an NE2571 chamber is almost identical to that calculated by Rogers[17,18] using TG-21 plus proposed corrections; however, in the case of a PR-06C chamber the difference between calculated and experimental values of $N_{D,w}^{^{60}\mathrm{Co}}/N_k$ is about 0.4%. Our results for two corresponding chambers are very consistent with their findings.[4,17,18]

For electron beams, in TG-51, the determination of k_Q is more complicated than for photon beams. Although the values of k_Q are also calculated at present, the new protocol allows future incorporation of measurements with primary standards in high-energy electron beams. Until measured values of k_Q (or k_{ecal}) become available, the uncertainty in absorbed dose determination according to TG-51 remains comparable to that according to TG-21 plus corrections for the water-to-air stopping-power ratios for realistic electron beams.[19]

Differences among the results in Table IV obtained by different methods are entirely due to the different values of $P_{\mathrm{wall}}^{^{60}\mathrm{Co}}$ and hence different values of k_{ecal} used. The recommended method of cross calibration in a high-energy electron beam agrees very well with the calculations when the measured $P_{\mathrm{wall}}^{^{60}\mathrm{Co}}$ for the NACP (#2) chamber is used. These uncertainties will be overcome in the future when the k_{ecal} factors for electron beams are provided by measurements with primary standards of absorbed dose in accelerator beams as discussed above.

In addition to the experimental comparison for electron beams, we have also investigated a calculational approach to the doses obtained using the two protocols. Although the calculational approach reduces the experimental calibration setup uncertainties, it is based on certain assumptions which in turn introduce some uncertainties. Our results have shown consistency between the calculational and the experimental approaches.

Another issue for electron beam calibration is that the new reference depth, d_{ref}, depends on R_{50}. Is the reference dose overly sensitive to changes in electron beam energy? The above question is particularly relevant to electron beams with incident energy greater than 12 MeV since the new reference depth will not be close to $d_{\max}$ and it may be at the descending part of the percentage-depth-dose curve. Our test results show that for a 20 MeV electron beam, if a beam energy is slightly varied but within the tolerance, e.g., the half-value depth varies by $\Delta R_{50}=3$ mm, the reference dose at d_{ref} differs by 0.7%. This indicates that it is important to measure R_{50} each time a calibration is performed, as discussed by Rogers.[10] The importance of measuring R_{50} also applies to electron beam calibration when the TG-21 protocol is used. According to the TG-21, the electron beam calibration also depends on R_{50} because the value of the stopping-power ratio at $d_{\max}$ is a function of the mean energy at the surface ($\bar{E}_0=2.33R_{50}$) and $d_{\max}$. It is worth mentioning that for some high-energy electron beams the portion of percentage-depth-dose curve near $d_{\max}$ is flat, therefore, the depth of $d_{\max}$ is not well defined. With a variation of 1 cm in depth of $d_{\max}$, the stopping-power ratio can vary by about 1%. Hence, the electron beam calibration using TG-21 includes such uncertainty as well.

V. CONCLUSIONS

This study shows that the differences in the determined absorbed dose to water at the reference point are within 1% for a ^{60}Co beam, 0.5% for photon beams with energies of 6 and 18 MV. For electron beams we have used different approaches to compare the dose changes at $d_{\max}$. The results are very similar when using the experimental approach or the calculational one. The results show that dose changes at $d_{\max}$ are within about 2%–3% between the two protocols for electron beams with energies of 6 to 20 MeV. There are five chambers, five photon beams from three different treatment units, and 13 electron beams from two different linear accelerators in this study. These results apply to those for which ionization chamber calibration factors ($N_{D,w}^{^{60}\mathrm{Co}}$ and N_x) are traceable to NRCC in Canada.

Our findings are consistent with the predictions by the AAPM TG-51 (Ref. 1) that, assuming TG-21 correctly predicts the ratio of absorbed dose to air kerma calibration factors, the implementation of the new protocol will not change the results of clinical reference dosimetry in photon beams by more than roughly 1% compared to those obtained by

following TG-21 (Ref. 2) for measurements in water. Slightly larger changes can be expected at d_{max} in electron beams because TG-51 (Ref. 1) protocol uses more accurate procedures regarding stopping-power ratios in realistic clinical electron beams[6,18] and also takes into account the improvements provided by the TG-39 (Ref. 7) protocol for plane-parallel chambers.

It can be seen that there may be no significant clinical consequences as a result of the implementation of the new AAPM TG-51 protocol. Nevertheless, it is important that these are tested in a clinical setting. It should also be noted that based on the study by Shortt *et al.*,[4] the NRC and NIST air-kerma standards in Canada and the U.S. differ by plus 0.6% and the absorbed-dose-to-water standards differ by minus 0.5%. Therefore, the change in relative dosimetry between Canada and the United States will be more than 1% as a result of the implementation of the new TG-51 protocol which starts the dosimetry dissemination chain with absorbed dose to water instead of air kerma. Therefore, the estimated dose changes in reference dosimetry are within 2% for a ^{60}Co beam, 1.5% for photon beams with energies of 6 and 18 MV, and 3%–4% for electron beams with energies of 6 to 20 MeV when chamber calibration factors ($N_{Dw}^{^{60}Co}$ and N_x) are traceable to NIST in the United States.

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