Reference dosimetry in clinical high-energy electron beams: Comparison of the AAPM TG-51 and AAPM TG-21 dosimetry protocols

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A comparison of the determination of absorbed dose to water in reference conditions with high-energy electron beams (E_{nominal} of 6, 8, 10, 12, 15, and 18 MeV) following the recommendations given in the AAPM TG-51 and in the original TG-21 dosimetry protocols has been made. Six different ionization chamber types have been used, two Farmer-type cylindrical (PTW 30001, PMMA wall; NE 2571, graphite wall) and four plane parallel (PTW Markus, and Scanditronix-Wellhöfer NACP, PPC-05 and Roos PPC-40). Depending upon the cylindrical chamber type used and the beam energy, the doses at $d_{\max}$ determined with TG-51 were higher than with TG-21 by about 1%–3%. Approximately 1% of this difference is due to the differences in the data given in the two protocols; another 1.1%–1.2% difference is due to the change of standards, from air-kerma to absorbed dose to water. For plane-parallel chambers, absorbed doses were determined by using two chamber calibration methods: (i) direct use of the ADCL calibration factors $N_{D,w}^{^{60}\mathrm{Co}}$ and N_X for each chamber type in the appropriate equations for dose determination recommended by each protocol, and (ii) cross-calibration techniques in a high-energy electron beam, as recommended by TG-21, TG-39, and TG-51. Depending upon the plane-parallel chamber type used and the beam energy, the doses at $d_{\max}$ determined with TG-51 were higher than with TG-21 by about 0.7%–2.9% for the direct calibration procedures and by 0.8%–3.2% for the cross-calibration techniques. Measured values of photon-electron conversion k_{ecal}, for the NACP and Markus chambers were found to be 0.3% higher and 1.7% lower than the corresponding values given in TG-51. For the PPC-05 and PPC-40 (Roos) chamber types, the values of k_{ecal} were measured to be 0.889 and 0.893, respectively. The uncertainty for the entire calibration chain, starting from the calibration of the ionization chamber in the standards laboratory to the determination of absorbed dose to water in the user beam, has been analyzed for the two formalisms. For cylindrical chambers, the observed differences between the two protocols are within the estimated combined uncertainty of the ratios of absorbed doses for 6 and 8 MeV; however, at higher energies ($10 \leqslant E \leqslant 18$ MeV), the differences are larger than the estimated combined uncertainties by about 1%. For plane-parallel chambers, the observed differences are within the estimated combined uncertainties for the direct calibration technique; for the cross-calibration technique the differences are within the uncertainty estimates at low energies whereas they are comparable to the uncertainty estimates at higher energies. A detailed analysis of the reasons for the discrepancies is made which includes comparing the formalisms, correction factors, and quantities in the two protocols, as well as the influence of the implementation of the different standards for chamber calibration.
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Key words: AAPM TG-51 protocol, AAPM TG-21 protocol, standards of absorbed dose to water, electron beam dosimetry, cylindrical ionization chamber, plane-parallel ionization chamber

I. INTRODUCTION

Task Group 51 of the Radiation Therapy Committee of the AAPM has published a new external beam dosimetry protocol that is based on the use of an ionization chamber calibrated in terms of absorbed dose to water in a standardslaboratory's ^{60}Co gamma ray beam.[1] The recommendations of this new protocol differ significantly from those given in most current dosimetry protocols, such as the AAPM TG-21[2] protocol or the IAEA Code of Practice (CoP) TRS 277,[3]

which are based on the exposure or air-kerma calibration factor of an ionization chamber in a ^{60}Co gamma ray beam and a $N_{\rm gas}$ (or $N_{D,\rm air}$) formalism for the determination of the absorbed dose to water in reference conditions.

The IAEA,[4] in collaboration with other international organizations (WHO, PAHO, and ESTRO), has also developed a new international Code of Practice that as well is based on the use of an ionization chamber calibrated in terms of absorbed dose to water in a standards laboratory's reference quality beam. The AAPM TG-51 protocol[1] and the IAEA CoP[4] follow those published by the German Standard DIN,[5] the British IPSM,[6] and the IAEA CoP for plane-parallel chambers,[7] that have discussed and implemented the procedures for the determination of absorbed dose to water based on standards of absorbed dose-to-water either in a ^{60}Co beam or in an accelerator beam.

As a change from TG-21 to TG-51 is recommended to users, it is important to evaluate the overall implications of this change at the clinic. Shortt *et al.*[8] have performed a comparison of absorbed dose to water and air-kerma calibration factors of a PR-06C and a NE2571 chamber in a ^{60}Co beam at the NRCC and NIST. Their study suggests an overall change of 1.1% in relative dosimetry between Canada and the United States as a result of using direct calibrations of ionization chambers in terms of absorbed dose to water (the TG-51 approach), $N_{D,w}^{^{60}\rm Co}$, instead of calibrations in terms of air kerma (or equivalently N_X, the TG-21 approach), N_K. In the same study, Shortt *et al.*[8] suggest that for clinical reference dosimetry the change from TG-21 to TG-51 may result in an increase of up to 2% depending upon the ion chamber used, the details of the protocol followed and the source of traceability, either NRCC or NIST.

Ding *et al.*[9] have recently performed a comparison of absorbed doses following TG-51 and TG-21 for high-energy photon and electron beams. They used ionization chambers with calibration factors in terms of exposure and absorbed dose to water in ^{60}Co, both traceable to NRCC. For photons, they performed an experimental comparison using a PR-06C and a NE2571 chamber in ^{60}Co, 6 and 18 MV beams. For electron beams they performed an experimental as well as a theoretical comparison. Their experimental comparison involved the use of one NACP-II chamber, whereas the theoretical comparison referred to the use of a NACP, a PTW Markus, and a PR-06C chamber. Their study estimated dose changes in reference dosimetry between TG-51 and TG-21 between 1.4 % and 2.2% for a ^{60}Co beam, between 0.8% and 1.5% for 6 and 18 MV photon beams, and between 0.9% and 3.3% (or 2.4%–4.4% for direct calibration) for electron beams with nominal energies of 6 to 20 MeV when the chamber calibrations ($N_{D,w}^{^{60}\rm Co}$ and N_X) had a ''derived'' traceablility to NIST. Huq and Andreo[10] have recently reported the results of a comparison of the recommendations of TG-51 and TG-21 for high-energy photon beams. At 6 and 18 MV, their results agree well with those of Ding *et al.*[9]

The experimental study of Ding *et al.*[9] involved the use of only one plane-parallel ionization chamber and their work did not identify the reasons for discrepancies that are due exclusively to the procedures and data recommended by the two protocols. The goals of the present work are twofold. Compare the TG-51[1] and the original TG-21[2] protocols by (i) performing a series of dosimetric measurements in clinical electron beams using different types of cylindrical and plane-parallel ionization chambers; this will provide the clinical physicists guidelines regarding the changes that can be expected when TG-51 is implemented in the clinic for electron beam calibrations using different types of ionization chambers, and (ii) identifying the reasons for discrepancies that are exclusively due to the data and procedures recommended by the two protocols separately from those that are solely due to the change of standards. To accomplish these goals, measurements were made with two widely used Farmer-type ionization chambers and four plane-parallel ionization chamber types in 6, 8, 10, 12, 15, and 18 MeV electron beams, obtained from an ELEKTA MLCi linear accelerator. Critical comparisons between the two protocols are performed and the sources of similarities and discrepancies identified.

II. METHODS

A strict comparison of the determination of absorbed dose to water in reference conditions using the recommended procedures given in the AAPM TG-51 and TG-21 protocols requires that both $N_{D,w}^{^{60}\rm Co}$ and N_X calibration factors be available for the chambers used in the comparison. In order to identify the reasons for discrepancies due exclusively to the procedures and data recommended by the two protocols, the assumption that the two types of calibration factors are exactly correlated will also be made and the $N_{D,w}^{^{60}\rm Co}$ calibration factor will be derived theoretically from N_X. For plane-parallel chambers theory alone cannot always be applied to determine $N_{D,w}^{^{60}\rm Co}$ from N_X . For the present work the calculated values of $N_{D,w}^{^{60}\rm Co}$ for the PPC-05 and PPC-40 chambers are based on experiments first to get $N_{\rm gas}$ for these two chambers. To enable the comparison of data in the two protocols, beam quality conversion factors (denoted by k_Q, see the following) will be derived from TG-21 data and the various contributing factors analyzed. It will then be possible to identify the changes due mainly to better data and new recommendations that are given in TG-51.[1]

According to the recommendations of TG-51, clinical reference dosimetry must be performed at a reference depth $d_{\rm ref}$ given by $d_{\rm ref}=0.6R_{50}-0.1$ (cm), while TG-21 recommends the depth of ionization maximum $I_{\rm max}$ (note this is not the depth of dose maximum $d_{\rm max}$). Since the present work is a comparison between two protocols, the depth of comparison should be the same in both cases; this depth is taken to be the depth of dose maximum $d_{\rm max}$. Comparison of the two protocols thus involve the following three steps:

(i) Determination of the absorbed dose to water at the depth of ionization maximum, $D_w^Q(I_{\rm max})$, using TG-21 and a N_X calibration factor, and then converting $D_w^Q(I_{\rm max})$ to the absorbed dose to water at the depth of maximum dose, $D_w^Q(d_{\rm max})$. This is accomplished by dividing $D_w^Q(I_{\rm max})$ by the

percent depth dose at the depth of ionization maximum, $\mathrm{PDD}(I_{\max})$.

(ii) Determination of the absorbed dose to water at the reference depth, $D_w^Q(d_{\mathrm{ref}})$, using TG-51 and a measured $N_{D,w}^{^{60}\mathrm{Co}}$ calibration factor, and then converting $D_w^Q(d_{\mathrm{ref}})$ to the absorbed dose to water at the depth of maximum dose, $D_w^Q(d_{\max})$. This is accomplished by dividing $D_w^Q(d_{\mathrm{ref}})$ by the clinical percent depth dose at the reference depth d_{ref}, $\mathrm{PDD}(d_{\mathrm{ref}})$.

(iii) Determination of the absorbed dose to water using TG-51 but calculating k_Q using the TG-21 data; further the calibration factor $N_{D,w}^{^{60}\mathrm{Co}}$ is derived theoretically from the N_X calibration factor.

According to TG-21 the absorbed dose to water at the depth of dose maximum in water, $D_w^Q(d_{\max})$, in an electron beam of quality Q, and in the absence of the chamber, is given by

$$D_w^Q(d_{\max}) = M(I_{\max})P_{\mathrm{gr}}(I_{\max})N_{\mathrm{gas}}(\overline{L}/\rho)_{\mathrm{gas}}^{w}P_{\mathrm{ion}}P_{\mathrm{fl}}P_{\mathrm{wall}} \times\left[\frac{1}{\mathrm{PDD}(I_{\max})}\right] \tag{1}$$

where $M(I_{\max})$ is the reading of the ionization chamber with the *point of measurement* of the chamber placed at the depth of ionization maximum $I_{\max}$, corrected for the effects of temperature, pressure, and polarity.

In TG-51 the absorbed dose to water at the depth of dose maximum in water, $D_w^Q(d_{\max})$, in an electron beam of quality Q, and in the absence of the chamber, is given by

$$D_w^Q(d_{\max}) = M(d_{\mathrm{ref}})P_{\mathrm{gr}}^Q(d_{\mathrm{ref}})k'_{R_{50}}k_{\mathrm{ecal}}N_{D,w}^{^{60}\mathrm{Co}}\left[\frac{1}{\mathrm{PDD}(d_{\mathrm{ref}})}\right]. \tag{2}$$

In Eq. (2) one defines $k_Q = P_{\mathrm{gr}}^Q k'_{R_{50}} k_{\mathrm{ecal}}$; $M(d_{\mathrm{ref}})$ is the reading of the dosimeter with the *point of measurement* of the chamber positioned at the reference depth d_{ref}, corrected for ion recombination, polarity effect, electrometer calibration factor, and to the standard environmental conditions of temperature, pressure, and relative humidity of the air in the ion chamber. The meaning of the other parameters that appear in Eqs. (1) and (2) can be found in the TG-21[2] and TG-51 protocols.[1]

An expression for the beam quality conversion factor k_Q has been given by Andreo,[11] Rogers,[12] and Huq and Andreo[10] as

$$k_Q = \frac{[(\overline{L}/\rho)_{\mathrm{air}}^{w}P_{\mathrm{gr}}P_{\mathrm{fl}}P_{\mathrm{wall}}P_{\mathrm{cel}}]_Q}{[(\overline{L}/\rho)_{\mathrm{air}}^{w}P_{\mathrm{gr}}P_{\mathrm{fl}}P_{\mathrm{wall}}P_{\mathrm{cel}}]_{^{60}\mathrm{Co}}}, \tag{3}$$

where $P_{\mathrm{repl}} = P_{\mathrm{gr}}P_{\mathrm{fl}}$. It should be noted that the equal symbol in Eq. (3) should strictly be replaced by the approximate symbol ($\approx$) to indicate the possible energy dependence of the W value.[4,10,11]

A. Relation between D_w^Q(TG-51) and D_w^Q(TG-21) at $d_{\max}$

Combining Eqs. (1), (2), and (3), the ratio of the absorbed doses between the two protocols at $d_{\max}$ can be written as

$$\begin{aligned} D_w^Q(d_{\max})\big|_{\text{TG-21}}^{\text{TG-51}} &= \frac{[M(d_{\mathrm{ref}})P_{\mathrm{gr}}^Q(d_{\mathrm{ref}})P_{\mathrm{fl}}^Q(d_{\mathrm{ref}})/\mathrm{PDI}^{\mathrm{NACP}}(d_{\mathrm{ref}})]_{\text{TG-51}}}{[M(I_{\max})P_{\mathrm{gr}}^Q(I_{\max})P_{\mathrm{fl}}^Q(I_{\max})/\mathrm{PDI}^{\mathrm{NACP}}(I_{\max})]_{\text{TG-21}}} \\ &\times \frac{[(\overline{L}/\rho)_{\mathrm{air}}^{w}(I_{\max})]_{\text{TG-51}}}{[(\overline{L}/\rho)_{\mathrm{air}}^{w}(I_{\max})]_{\text{TG-21}}} \frac{[P_{\mathrm{wall}}(^{60}\mathrm{Co})]_{\text{TG - 21}}}{[P_{\mathrm{wall}}(^{60}\mathrm{Co})]_{\text{TG-51}}} \\ &\times \frac{[P_{\mathrm{cel}}|_{^{60}\mathrm{Co}}^{Q}]_{\text{TG-51}}}{1} \frac{N_{D,w}^{^{60}\mathrm{Co}}(\mathrm{measured})}{N_{D,w}^{^{60}\mathrm{Co}}(\mathrm{calculated})}, \end{aligned} \tag{4}$$

where the PDD at a given depth has been written as the product of the percent depth ionization, $\mathrm{PDI}^{\mathrm{NACP}}$ measured by using the NACP plane-parallel chamber, and the water-to-air stopping power ratios, $(\overline{L}/\rho)_{\mathrm{air}}^{w}$, at that depth for the beam quality Q. Since the percent depth ionization curves used in the present study were measured using a well-guarded NACP chamber, no chamber dependent correction factors are needed to convert the depth ionization curves to depth dose curves. The values of $(\overline{L}/\rho)_{\mathrm{air}}^{w}$ used for the conversion of the PDI curve to the PDD curve are those for realistic electron beams taken from TG-51. In deriving Eq. (4), the values of $P_{\mathrm{gr}}^{^{60}\mathrm{Co}}$ have been taken to be the same for both protocols and $P_{\mathrm{fl}}(^{60}\mathrm{Co})$ has been taken to be unity. The value of $N_{D,w}^{^{60}\mathrm{Co}}(\mathrm{measured})$ for each chamber type is that obtained from the Accredited Dosimetry Calibration Laboratory (ADCL) and the value of $N_{D,w}^{^{60}\mathrm{Co}}(\mathrm{calculated})$ is obtained from[2,4,10,11]

$$N_{D,w}^{^{60}\mathrm{Co}}(\mathrm{calculated}) = N_{\mathrm{gas}}[(\overline{L}/\rho)_{\mathrm{gas}}^{w}P_{\mathrm{gr}}P_{\mathrm{fl}}P_{\mathrm{wall}}]_{^{60}\mathrm{Co}}. \tag{5}$$

TG-21 does not incorporate a correction term for the lack of air equivalence of the aluminum central electrode for cylindrical ionization chambers in its formalism. Consequently, such a factor for TG-21 does not appear in Eq. (4) in this paper. The subscripts TG-21 or TG-51 for each factor in Eq. (4) indicate that the values of the appropriate factors should be evaluated by using the data given in the TG-21 or the TG-51 protocols, respectively.

B. Use of plane-parallel chambers

According to TG-51, plane-parallel chambers must be used for reference dosimetry in electron beams of energies 6 MeV or less. At higher energies their use is recommended but not required. For reference dosimetry, the protocol allows for the use of plane-parallel chambers that have been calibrated in terms of absorbed dose to water 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,[13] the protocol recommends that, when possible, the absorbed dose to water calibration factor of a plane-parallel chamber be determined by cross calibrating it against a calibrated cylindrical ionization chamber in a

TABLE I. Characteristics of the cylindrical chambers. The N_X and $N_{D,w}^{^{60}Co}$ calibration factors were provided by the ADCL K & S Associates, Inc. Nashville, TN.

Chamber type	Cavity volume (cm^3)	Cavity length (mm)	Cavity radius (mm)	Wall material	Wall thickness ($g\,cm^{-2}$)	Central electrode material	N_X (10^9R/C)	N_{gas} (10^7Gy/C)	$N_{D,w}^{^{60}Co}$ (10^7Gy/C)
NE2571 Sl#2415	0.6	24.0	3.10	Graphite	0.065	Al	4.680	3.990	4.525
PTW 30001 Sl#1340	0.6	23.0	3.05	PMMA[a]	0.045	Al	5.513	4.677	5.330

[a]Like most chamber types with nonconductive plastic walls, the chamber wall has an inner conductive layer made of graphite. For this chamber type, the thickness and density of the graphite layer is supplied in the chamber specifications.

high-energy electron beam. The cross-calibration technique determines the product $k_{ecal}N_{D,w}^{^{60}Co}$ for the plane-parallel chambers from the relation

$$[k_{ecal}N_{D,w}^{^{60}Co}]^{pp}=\frac{[MP_{gr}^{Q_{cross}}k'_{R50}(Q_{cross})k_{ecal}N_{D,w}^{^{60}Co}]^{cyl}}{[Mk'_{R50}(Q_{cross})]^{pp}}, \quad (6)$$

where Q_{cross} is the electron beam energy at which the cross calibration is performed. The protocol describes the procedure for performing the cross calibration.

The AAPM TG-39 protocol[14] also recommends the use of a cross-calibration technique in a high-energy electron beam as the preferred method for determining N_{gas} for plane-parallel chambers. According to the recommendations of TG-39, the N_{gas} for a plane-parallel chamber is obtained from

$$N_{gas}^{pp}=\frac{[MN_{gas}P_{ion}P_{gr}P_{fl}]^{cyl}}{[MP_{ion}P_{fl}]^{pp}}. \quad (7)$$

The values of $k_{ecal}N_{D,w}^{^{60}Co}$, and N_{gas}^{pp} obtained from Eq. (6) and (7) can then be used in Eqs. (2) and (1) and the ratios of absorbed doses determined by the two protocols at d_{max} are obtained from Eq. (4).

C. Experimental method

Six different ionization chamber types have been used for the present study. These include two Farmer-type chambers and four plane-parallel chamber types. The Farmer-type chambers are a PTW 30001 with PMMA wall and a NE 2571 with graphite wall; the plane-parallel chamber types are a Markus chamber made by PTW, and well-guarded NACP, PPC-40 (Roos), and PPC-05 chambers made by Scanditronix-Wellhöfer. For all six chamber types, the $N_{D,w}^{^{60}Co}$ and N_X calibration factors were obtained from an ADCL (K & S Associates, Inc. Nashville, TN). Additionally, $k_{ecal}N_{D,w}^{^{60}Co}$ and N_{gas}^{pp} for all plane-parallel chambers were obtained by cross calibrating them against the calibrated NE2571 chamber in an 18 MeV electron beam. Details of the chamber characteristics and their calibration factors are given in Tables I and II.

The electron beams were generated by an Elekta MLCi linear accelerator. All depth-ionization, calibration, and cross-calibration measurements were made in a Scanditronix-Wellhöfer water tank for a field size of 20 cm×20 cm and a SSD of 100 cm. The movement of the chambers was controlled by a Wellhöfer WP700 computerized beam scanner. Depth ionization measurements along the central axis were made by using the NACP chamber. For the absolute dose measurements the position of the ionization chambers was also verified directly. The uncertainty of the positioning of the chamber at a certain depth is ±0.3 mm. For all depth ionization measurements, the ratio of the net ionization from the scanning and reference detectors and the spatial information of the scanning detector were recorded by the Wellhofer WP700 system. Analysis of the data taken by the beam scanner was done using the same system. The accuracy of the alignment of the scanner central axis with the beam central axis was always better than 1 mm. Prior to taking all measurements, the ion chambers and the phantom were allowed to equilibrate with ambient air at room temperature for more than 24 h.

The beam quality in TG-51[1,15] is specified by R_{50}, which is the depth in water at which the absorbed dose falls to 50% of the maximum dose, determined from ionization measurements in conjunction with an equation that relates ionization and dose. On the other hand, the mean energy at the phantom surface, $\overline{E_0}$, and the depth in water are needed to specify the beam quality in TG-21.[2] The values of R_{50} were obtained from[1] $R_{50}=1.029\ I_{50}-0.063$ [cm] and those for $\overline{E_0}$ from[2] $\overline{E_0}=2.33\ I_{50}$ where I_{50} is the depth of 50% ionization.

TABLE II. Characteristics of the plane-parallel chambers. The N_X and $N_{D,w}^{^{60}Co}$ calibration factors were provided by ADCL K & S Associates, Inc. Nashville, TN. The N_{gas}^{pp} and $k_{ecal}N_{D,w}^{^{60}Co}$ were obtained by cross calibration against the calibrated NE 2571 chamber in an 18 MeV electron beam.

Chamber type	Window thickness	Electrode spacing (mm)	Collecting electrode diameter (mm)	Guard ring width (mm)	N_X (10^{10}R/C)	$N_{D,w}^{^{60}Co}$ (10^8Gy/C)	N_{gas}^{pp} (from cross calibration) (10^8Gy/C)	$k_{ecal}N_{D,w}^{^{60}Co}$ (10^8Gy/C)
PTW Markus	102 mg cm^{-2}	2.0	5.3	0.2	5.523	5.448	4.660	4.849
NACP[a]	0.6 mm	2.0	10	3	1.629	1.602	1.363	1.428
PPC-05[a]	1 mm	0.6	10	3.5	5.570	5.482	4.659	4.873
PPC-40[a]	1 mm	2.0	16	4	0.9836	0.9717	0.8259	0.8680

[a]Made by Scanditronix–Wellhöfer.

TABLE III. Beam characteristics and water-to-air stopping power ratios for electron beams.

Energy (MeV)	I_{max} (cm)	I_{50} (cm)	$\overline{E_0}$ (MeV)	R_{50} (cm)	d_{ref} (cm)	d_{max} (cm)	PDI at (I_{max})	PDI at (d_{ref})	$(\overline{L}/\rho)^{w}_{air}$ at I_{max} [a]	$(\overline{L}/\rho)^{w}_{air}$ at d_{ref} [b]
6	1.19	2.40	5.59	2.41	1.35	1.3	100	99.2	1.073	1.074
8	1.51	3.15	7.34	3.18	1.81	1.7	100	98.9	1.057	1.063
10	2.05	4.05	9.44	4.11	2.36	2.2	100	99.0	1.046	1.052
12	2.16	4.54	10.76	4.61	2.67	2.4	100	98.6	1.037	1.047
15	1.79	5.76	13.42	5.87	3.42	2.8	100	96.6	1.005	1.036
18	2.00	6.56	15.29	6.69	3.91	3.2	100	96.8	0.997	1.030

[a]Calculated using the data for monoenergetic electrons given in the TG-21 protocol.
[b]Calculated for realistic electrons using Eq. (3) of Burns *et al.* (Ref. 12).

Although TG-21 recommends that the central axis of a cylindrical chamber be placed at the depth of ionization maximum, in the present study the *effective point of measurement* of the cylindrical chambers was placed at the reference depth of ionization maximum I_{max}. This is because at low electron beam energies ($6 \leqslant E \leqslant 12$ MeV) the shifted ionization maximum of a depth-ionization curve measured by a cylindrical ionization chamber[16] coincides with the ionization maximum measured by the NACP chamber. At the highest electron beam energies the depth ionization curve has a broad maximum and the corrections resulting from gradient effects are negligible. For plane-parallel chambers, the *point of measurement* was placed at the depth of I_{max} for TG-21 dosimetry. For the TG-51 dosimetry, all measurements were done by placing *the point of measurement* of the ionization chambers at the reference depth d_{ref}. These measurements were corrected for the gradient effect, P^{Q}_{gr}, when cylindrical chambers were used for the measurements. For cross-calibration measurements, the *point of measurement* of all chambers was placed at the depth of ionization maximum for TG-21 dosimetry and at the depth of d_{ref} for TG-51 dosimetry. *The point of measurement* for cylindrical chambers is taken to be on the chamber axis at the center of the cavity volume; for plane-parallel chambers it is taken to be on the inner surface of the entrance window, at the center of the window.

Data presented here correspond to the average of at least six readings, more typically eight readings per point. Half of the readings were taken with positive polarity and half with negative polarity. The recommendations of each protocol were followed to correct the ionization chamber readings for ion recombination, electrometer calibration factor, and to the standard environmental conditions of temperature, pressure, and relative humidity of the air in the ion chamber. All ionization measurements were referenced to that of a 0.3 cm^3 PTW chamber mounted on the head of the machine. This circumvents the problems associated with instabilities in machine output and monitor response. When referenced to the 0.3 cm^3 PTW monitor chamber, the measurements were repeatable to within $\pm 0.2\%$. A description of the estimated relative standard uncertainties in the determination of absorbed doses is given in Sec. V.

III. RESULTS

Equations (1) and (2) have been used for the calculations of absorbed dose to water for the AAPM TG-21 and TG-51 protocols respectively. Equation (5) has been used for the calculations of $N^{^{60}Co}_{D,w}$ from N_X and Eq. (4) for the calculations of ratios of doses determined with TG-51 and TG-21. In the analysis of the data the influences of the contribution from various correction factors, as well as that from the calibration factors of ionization chambers based on different standards, are considered separately.

Table III gives the electron beam characteristics used in the present study as well as the calculated values of water-to-air stopping power ratios at the depths of I_{max} and d_{ref}. The water-to-air stopping power ratios at I_{max} are for monoenergetic electrons and these values have been taken from TG-21. On the other hand, the water-to-air stopping power ratios at d_{ref} apply to realistic electron beams and these values have been calculated using Eq. (3) of Burns *et al.*[15]

A comparison of the results of the absorbed doses to water at d_{max}, determined according to the recommendations of TG-51 and TG-21, is given in Table IV for the two cylindrical chambers and the various electron beam energies investigated in this study. The TG- 21 doses in column 5 were determined by placing the *effective point of measurement* of the cylindrical chambers at the depths of ionization maximum I_{max} and incorporating the gradient correction at I_{max}, $P_{gr}(I_{max})$, to the charge reading. On the other hand, the TG-21 doses in column 3 were determined by placing the central axis of the chambers at I_{max} and without incorporating any gradient correction to the charge reading. The gradient corrections were measured by following the procedure recommended in TG-51.[1] As can be seen from Table IV, the gradient effect can cause differences of up to 1.1% at low energies for TG-21 dosimetry. It should be pointed out that TG-21 recommends using a value of unity for $P_{gr}(I_{max})$ at I_{max} for electron beam calibrations. The present study shows that this recommendation will be incorrect when a cylindrical ionization chamber is used with a depth-ionization curve measured by using a plane-parallel ionization chamber.

The ratios of the absorbed doses at d_{max} given in column 5 of Table IV were used for the absorbed dose comparison between the two protocols. Table IV also gives the numerical values of the ratios of the various factors that appear in Eq. (4). Depending upon the beam energy or the chamber used, the doses determined according to TG-51 are found to be higher than those determined according to TG-21 by about 1%–3%.

Table V gives the results for all plane-parallel chamber types and beam energies investigated in this study. Column 7

TABLE IV. Ratios of absorbed doses to water at d_{max} and various factors that appear in Eq. (4) for cylindrical chambers. The values of all factors at d_{ref} are evaluated by using the data from TG-51 and those at I_{max} are evaluated by using the data given in the original TG-21 protocol. (Ref. 2).

Energy (MeV)	Chamber type	$D_w^Q(d_{max})\|_{TG-21}^{TG-51}$ without P_{gr} at I_{max}	P_{gr} at I_{max}	$D_w^Q(d_{max})\|_{TG-21}^{TG-51}$ Eff pt at I_{max} Eqs. (1) and (2)	$D_w^Q\|_{TG-21}^{TG-51}$ at d_{max} from factors	$(MP_{gr}^Q P_{fl}^Q/PDI)\|_{Im\ ax}^{dref}$	$(\bar{L}/\rho)_{air}^{w}\|_{TG-21}^{TG-51}$ at I_{max}	$P_{wall}\|_{TG-51}^{TG-21}$ at ^{60}Co	$P_{cell}\|_{60Co}^{Q}$ at d_{ref}	$\frac{N_{D,w}^{60Co}(meas)}{N_{D,w}^{60Co}(cal)}$
6	NE2571	1.029	1.011	1.018	1.020	1.002	0.995	1.005	1.007	1.011
	PTW30001	1.018	1.009	1.010	1.012	0.996	0.995	1.002	1.007	1.012
8	NE2571	1.021	1.005	1.016	1.017	0.997	0.997	1.005	1.007	1.011
	PTW3001	1.023	1.007	1.016	1.016	0.998	0.997	1.002	1.007	1.012
10	NE2571	1.032	1.005	1.027	1.028	1.006	0.999	1.005	1.007	1.011
	PTW30001	1.029	1.004	1.024	1.025	1.005	0.999	1.002	1.007	1.012
12	NE2571	1.030	1.003	1.027	1.028	1.005	1.000	1.005	1.007	1.011
	PTW30001	1.028	1.003	1.024	1.026	1.005	1.000	1.002	1.007	1.012
15	NE2571	1.027	1.000	1.028	1.028	1.003	1.004	1.005	1.005	1.011
	PTW30001	1.032	1.001	1.031	1.031	1.008	1.004	1.002	1.005	1.012
18	NE2571	1.031	1.000	1.031	1.031	1.006	1.004	1.005	1.005	1.011
	PTW30001	1.028	1.001	1.026	1.027	1.004	1.004	1.002	1.005	1.012

gives the results for the ratios of absorbed doses $D_w^Q(d_{max})\|_{TG-21}^{TG-51}$ determined for each chamber and electron beam energy using the direct calibration procedure. For TG-51 dosimetry, this involves the determination of absorbed dose using the ADCL calibrated $N_{D,w}^{60Co}$ factor for each chamber and Eq. (2). On the other hand, the direct calibration procedure in TG-21 dosimetry involves the determination of N_{gas}^{pp} from N_X and A_{ion}, and the information given in Table I of TG-39[14] together with Eq. (1). Since Table I of TG-39 does not contain any information for the PPC-40 and PPC-05 chambers, the dose comparison entries for these chambers in column 7 of Table V are kept blank. Column 8 compares the ratios of absorbed doses determined by the two protocols at d_{max} where the $D_w^Q(d_{max})$ values for each chamber were determined by following the cross-calibration procedure described in Sec. II B. Depending upon the chamber and electron beam energy used, the $D_w^Q(d_{max})\|_{TG-21}^{TG-51}$ values for the direct calibration procedures are found to lie between 1.007 and 1.029 and those for the cross-calibration procedures are found to lie between 1.008 and 1.032.

The cross-calibration procedure described in TG-51 enables the determination of the product $k_{ecal}N_{D,w}^{60Co}$ for plane-parallel chambers. If the value of $N_{D,w}^{60Co}$ for a given plane-

TABLE V. Ratios of absorbed doses at d_{max} to water and other factors that appear in Eq. (4) for plane-parallel chambers.

Energy (MeV)	Chamber type	$(MP_{gr}^Q P_{fl}^Q/PDI)\|_{Im\ ax}^{d_{ref}}$	$(\bar{L}/\rho)_{air}^{w}(I_{max})\|_{TG-21}^{TG-51}$	$\frac{N_{D,w}^{cross}(TG-51)}{N_{D,w}^{cross}(TG-21)}$	$\|D_w^Q(d_{max})\|_{TG-21}^{TG-51}$ From factors	Direct determination	Cross calibration
6	Markus	1.003	0.995	1.016	1.012	1.012	1.012
	NACP	1.002	0.995	1.022	1.019	1.008	1.019
	PPC-40	1.000	0.995	1.027	1.021	⋯	1.020
	PPC-05	0.993	0.995	⋯	⋯	⋯	1.008
8	Markus	1.009	0.997	1.016	1.020	1.020	1.020
	NACP	0.998	0.997	1.022	1.018	1.007	1.018
	PPC-40	1.002	0.997	1.027	1.026	⋯	1.025
	PPC-05	0.997	0.997	⋯	⋯	⋯	1.015
10	Markus	1.004	0.999	1.016	1.018	1.019	1.019
	NACP	1.005	0.999	1.022	1.026	1.016	1.027
	PPC-40	1.002	0.999	1.027	1.027	⋯	1.026
	PPC-05	1.002	0.999	⋯	⋯	⋯	1.021
12	Markus	1.004	1.000	1.016	1.019	1.020	1.020
	NACP	1.004	1.000	1.022	1.026	1.016	1.027
	PPC-40	1.000	1.000	1.027	1.026	⋯	1.025
	PPC-05	1.001	1.000	⋯	⋯	⋯	1.022
15	Markus	1.003	1.004	1.016	1.021	1.021	1.021
	NACP	1.002	1.004	1.022	1.028	1.017	1.028
	PPC-40	0.998	1.004	1.027	1.029	⋯	1.028
	PPC-05	1.002	1.004	⋯	⋯	⋯	1.026
18	Markus	1.011	1.003	1.016	1.029	1.029	1.030
	NACP	1.004	1.003	1.022	1.030	1.020	1.030
	PPC-40	1.002	1.003	1.027	1.033	⋯	1.032
	PPC-05	1.006	1.003	⋯	⋯	⋯	1.030

TABLE VI. Values of k_{ecal} for plane-parallel chambers.

Chamber type	k_{ecal} (TG-51)	k_{ecal} (cross calibration)	% difference
Markus	0.905	0.890	−1.7
NACP	0.888	0.891	0.3
PPC-40	0.901[a]	0.893	−0.8[a]
PPC-05	⋯	0.889	⋯

[a]The value of 0.901 is applicable to the prototype of the Roos chamber made by PTB (Ref. 1).

parallel chamber is available from the ADCL then from the knowledge of $k_{ecal}N_{D,w}^{^{60}Co}$ one can determine the value of k_{ecal} for that particular chamber. The experimentally determined values of k_{ecal} for the four plane-parallel chamber types are given in Table VI. The measured values of k_{ecal} for the NACP and Markus chambers are found to be 0.3% higher and 1.7% lower than the corresponding values given in the TG-51 protocol. For the PPC-40 and PPC-05 chambers, the measured values of k_{ecal} are 0.893 and 0.889, respectively. For the PPC-40 this can be compared with the value of 0.901 given in TG-51 for the Roos-PTB chamber.

As a check of the experimental methodology and chamber performance, the dose at I_{max}, measured with the two cylindrical chambers according to the recommendations of TG-21 were compared against each other. The ratios of $|D_w^Q(I_{max})|_{TG\text{-}21}$ between the NE and PTW chambers are 0.993, 0.995, 0.996, 0.997, 0.996, and 0.999 for 6, 8, 10, 12, 15, and 18 MeV, respectively. The corresponding results for $|D_w^Q(d_{ref})|_{TG\text{-}51}$ are 1.002, 0.995, 0.999, 0.999, 0.994, and 1.003. These ratios indicate that the overall consistency of the protocols for different chambers, combined with the repeatability of our measurements, is better than ±0.7%.

IV. DISCUSSION

A. Influence of various correction factors

In order to enable a comparison of the absorbed doses to water between the two protocols and provide a convenient means of identifying the relative contributions of each factor to the absorbed dose, calculations were performed by following the method described in step (iii) in Sec. II. This involves the calculation of k_Q values determined using data from TG-21 and the use of a theoretically derived $N_{D,w}^{^{60}Co}$. A theoretically derived $N_{D,w}^{^{60}Co}$ is used in the dose calculation to illustrate the differences that arise exclusively due to protocols and not due to the type of standards used. These results are compared to the corresponding factors in TG-51 in Tables IV and V, where parameters from both protocols [see Eq. (4)], which are similar in meaning, have been grouped together.

It can be seen from Tables IV and V that there are several components that contribute to the observed differences in absorbed dose between the two protocols. These are (i) the uncertainty in the charge readings measured at d_{ref} and at I_{max}, which is intrinsic to the measurement procedure and common to the two protocols, (ii) the differences between the realistic and monoenergetic water-to-air stopping power ratios used in the two protocols, (iii) the wall correction factors, (iv) the central electrode correction factor, (v) the differences between the measured and calculated values of the absorbed dose-to-water calibration factor, $N_{D,w}^{^{60}Co}$, of the ionization chambers, and (vi) the differences in the measured values of the absorbed dose to water calibration factors, $N_{D,w}^{cross}$, obtained from cross calibration for plane-parallel chambers.

The term

$$\frac{[M(d_{ref})P_{gr}^Q(d_{ref})P_{fl}^Q(d_{ref})/\mathrm{PDI}^{NACP}(d_{ref})]_{TG\text{-}51}}{[M(I_{max})P_{gr}^Q(I_{max})P_{fl}^Q(I_{max})/\mathrm{PDI}^{NACP}(I_{max})]_{TG\text{-}21}}$$

in Eq. (4) and in Tables IV and V reduces to

$$\frac{[M(d_{ref})P_{gr}^Q(d_{ref})/\mathrm{PDI}(d_{ref})]}{[M(I_{max})P_{gr}^Q(I_{max})/\mathrm{PDI}(I_{max})]}$$

for any chamber and has a value equal to unity. Deviations of this quantity from unity in Tables IV (column 7) and V (column 3) correspond to type B uncertainties of 0.4% in the measurement of the charge.

The various components that contribute to the observed differences between the two protocols are discussed in detail in the following.

1. Cylindrical chambers

The water-to-air stopping power ratios, $[(\overline{L}/\rho)_{air}^{w}(I_{max})]$, used in TG-51 are those for realistic electron beams. On the other hand, the values of $[(\overline{L}/\rho)_{air}^{w}(I_{max})]$ used in TG-21 are for monoenergetic electron beams. These two sets of values have been calculated using different Monte Carlo codes (ETRAN and EGS4) that differ in their results for monoenergetic electron beams by up to 1% for shallow depths and slightly less for depths beyond $0.2r_0$,[7,17,18] where r_0 is the electron continuous slowing down approximation (csda) range. Using the BEAM code Ding *et al.*[19] have shown that the TG-21 stopping power ratios at d_{max} together with a relation for the mean energy at the surface[20] more accurate than that used in TG-21, overestimate the realistic stopping power ratios by up to 0.5% for a 5 MeV beam and underestimate them by up to 1.2% for a 20 MeV beam. The present work, however, shows that the TG-51 stopping power ratios are higher than those applying TG-21 by 0.4% at the depth of I_{max} for an 18 MeV electron beam. The differences decrease slowly as the energy is decreased and at 6 MeV the TG-51 values become lower than the TG-21 stopping power ratios by 0.5%. The differences between TG-51 and TG-21 stopping power ratios reported earlier[19] cannot thus solely be attributed to the use of monoenergetic versus "realistic" data, but the selection procedure also has to be taken into account. It is interesting that the net changes resulting from using different Monte Carlo codes and simple (plane-parallel geometry) versus complicated (detailed accelerator head simulation) calculations are not larger than ±0.5% when stopping power ratios are selected according to the original recommendations of the two protocols.

The fluence correction factor P_{fl} accounts for the change in electron fluence that occurs due to the replacement of

phantom material by the chamber cavity. This correction depends on the beam energy at the point of measurement and on the inner radius of the cavity. Values of P_{fl} are only known at d_{max} and the assumption is made that these values apply at d_{ref}.[12] The validity of this assumption has been confirmed by Huq *et al.*[21] Because the same data set is used by both protocols, P_{fl}^{Q} does not contribute to the observed differences in the absorbed dose between the two protocols at the same depth.

Both protocols use the expression developed by Almond and Svensson[22] for the calculation of P_{wall}, at ^{60}Co. In the TG-51 calculations of $(P_{wall})_{^{60}Co}$ the stopping power ratios have been taken from Rogers and Yang[23] whereas $\overline{(\mu_{en}/\rho)}$ ratios have been taken from IAEA TRS 277.[3] The values of the parameter α required for the calculations of $(P_{wall})_{^{60}Co}$ have been taken from Lempert *et al.*[24] by both protocols. When the TG-51 values of $(P_{wall})_{^{60}Co}$ are compared with the corresponding values obtained from TG-21, a discrepancy of up to 0.5% is observed, which results from the use of different data sets in the two protocols.

For cylindrical chamber types, P_{cel} corrects for the lack of air equivalence of the central electrode. TG-51 incorporated the effect of aluminum central electrode of diameter 1 mm on the response of a Farmer-type ionization chamber. TG-21 does not include any such correction factors in its formalism. For the chambers and electron beam energies employed in this study, the effect of the central electrode is to increase the TG-51 value of D_{w}^{Q} by 0.7% for $6 \leqslant E \leqslant 12$ MeV and by 0.5% for $E=15$ and 18 MeV.

It is important to emphasize that the product of the stopping power ratios and perturbation correction factors (factors in columns 8–10 in Table IV for each chamber/ energy combination) results in a net increase which in no case is larger than 1.0%. This is the difference that can be solely attributed to the data and procedures recommended in TG-51 compared with TG-21. Another 1.1%–1.2% difference between the two protocols occurs due to the change of standards of air-kerma to standards of absorbed dose to water in ^{60}Co beams.

2. Plane-parallel chambers

For plane-parallel chambers $P_{gr}^{Q}=1$ and for well-guarded plane-parallel chambers $P_{fl}^{Q}=1$. The constructional details of the PPC-40 and PPC-05 chambers meet the requirements of the construction of a well-guarded plane-parallel chamber.[7] Therefore, it is assumed that these two chambers have a P_{fl}^{Q} value of unity. Column 6 of Table V is obtained from the multiplication of all factors that appear in columns 3–5. The data shown in column 7 have been obtained from direct calibration and those in column 8 from cross calibration. The differences in results between columns 6 and 8 are all accounted for by the differences between $k'_{R50}k_{ecal}$ values calculated with the factors used in this study and the fitted formula given in TG-51. A comparison of the present results with those of Ding *et al.*[9] for the NACP chamber shows that for the cross-calibration procedure the present results are about 1% higher than those of Ding *et al.*[9] On the other hand, for the direct calibration procedure the results of Ding *et al.*[9] are higher than the present results by about 1.5%–3%. The reasons for the discrepancy between the present data and those of Ding *et al.*[9] for the direct calibration procedure cannot be clarified at this stage.

In order to analyze the details of the difference observed for $N_{D,w}^{cross}|_{TG\text{-}21}^{TG\text{-}51}$ one defines

$$N_{D,w}^{cross}|_{TG\text{-}21}^{TG\text{-}51}=\frac{[k_{ecal}N_{D,w}^{^{60}Co}]^{pp}}{k_{ecal}}\frac{1}{N_{gas}^{pp}[(\overline{L}/\rho)_{air}^{w}P_{repl}P_{wall}]_{^{60}Co}}$$

$$=\frac{N_{D,w}^{^{60}Co,Cyl}(\mathrm{ADCL})}{N_{D,w}^{^{60}Co,Cyl}(N_X)}\frac{M^{Cyl}P_{gr}|_{Im\ ax}^{d_{ref}}}{M^{pp}P_{gr}|_{Im\ ax}^{d_{ref}}}$$

$$\times\left[\frac{P_{cel}^{Q}(d_{ref},\mathrm{Cyl})}{P_{cel}^{^{60}Co}}\right]^{TG\text{-}51}[P_{wall}(^{60}\mathrm{Co,Cyl})]\Big|_{TG\text{-}51}^{TG\text{-}21}$$

$$\times\left[\frac{P_{fl}^{Q}(\mathrm{TG\text{-}51},d_{ref})}{P_{fl}^{Q}(\mathrm{TG\text{-}21},I_{max})}\right]\Big|_{pp}^{cyl}, \tag{8}$$

where $N_{D,w}^{^{60}Co,Cyl}(\mathrm{ADCL})$ denotes the absorbed dose to water calibration factor of a cylindrical chamber obtained from ADCL; $N_{D,w}^{^{60}Co,Cyl}(N_X)$ denotes that the $N_{D,w}^{^{60}Co}$ factor of the cylindrical chamber that has been calculated through the chain $N_X \rightarrow N_{gas} \rightarrow N_{D,w}^{^{60}Co}$. The first term on the right-hand side of Eq. (8) denotes differences between the measured and the calculated values of the absorbed dose-to-water calibration factor, $N_{D,w}^{^{60}Co}$, for the NE 2571 chamber; the second term differs from unity due to the uncertainties in the charge measurement and in P_{gr}; the third term accounts for the fact that TG-51 incorporates a central electrode correction for aluminum central electrodes of cylindrical chambers which TG-21 does not; the fourth term identifies the contribution from P_{wall} because different data sets were used by both protocols for its evaluation for cylindrical chambers at ^{60}Co; and the last term identifies contributions from fluence correction factors.

The numerical values of the various factors that appear in Eq. (8) have been tabulated for the PTW Markus, PPC-40, and NACP chambers in Table VII for an 18 MeV electron beam since that is the energy at which all cross calibrations were performed. The k_{ecal} value needed for the calculations for the PPC-40 chamber is assumed to be the same as that of the PTB/Roos chamber.[1] It can be seen from Table VII that differences in the measured and calculated values of $N_{D,w}^{^{60}Co}$ contribute 1.1%, the charge measurements contribute 1.0% for the NACP chamber and 0.4% for the Markus chamber, the central electrode contributes 0.5%, the P_{wall} contributes 0.5%, and the differences in fluence correction factors between NE2571 and the plane-parallel chambers contribute a factor of 0.99 for the Markus chamber and 0.992 for the NACP chamber.

The Markus chamber is not regarded as a well-guarded chamber. TG-39 recommended a nonunity value of P_{fl}^{Q} for this chamber at I_{max} for low energy electron beams. Ratios of P_{fl}^{Q} at d_{ref} and I_{max} contribute up to a difference of 0.2% between the two protocols.

TABLE VII. Ratios of various factors that appear in Eq. (8) for plane-parallel chambers.

Energy (MeV)	Chamber type	$\frac{N_{D,w}^{\text{cross}}(\text{TG-51})}{N_{D,w}^{\text{cross}}(\text{TG-21})}$	First term of Eq. (8)	Second term of Eq. (8)	Third term of Eq. (8)	Fourth term of Eq. (8)	Fifth term of Eq. (8)
18	Markus	1.016	1.011	1.004	1.005	1.005	0.990
	PPC-40	1.027	1.011	1.013	1.005	1.005	0.992
	NACP	1.022	1.011	1.010	1.005	1.005	0.992

B. Influence of the calibration factor based on different standards

As shown in Table IV, the difference between the measured and calculated values of $N_{D,w}^{^{60}\text{Co}}$ has one of the largest effects on the observed differences in the absorbed dose to water between the two protocols. The measured value of $N_{D,w}^{^{60}\text{Co}}$ is higher than the calculated value by 1.2% for the PTW chamber and 1.1% for the NE chamber. Ding *et al.*[9] have reported that for calibrations of ^{60}Co beams based on standards of air-kerma and of absorbed dose to water, the dose measured according to TG-51 is higher than that of TG-21 by 1.4% when a NE 2571 chamber is used. These results were based on the study by Shortt *et al.*[8] Measurements at the IAEA Dosimetry Laboratory[4] using various ionization chambers have shown that at ^{60}Co, the absorbed dose to water determined by using measured values of $N_{D,w}^{^{60}\text{Co}}$ is about 1% higher than that determined by using the air-kerma calibration factor N_K together with IAEA TRS 277.[3] Huq and Andreo[10] and Andreo *et al.*[4] have given a detailed discussion on this discrepancy.

The difference at ^{60}Co is transported into the comparisons at high-energy electron beams, establishing a systematic difference between the absorbed dose to water using the $N_{D,w}$ and K_{air} or X-based dosimetry protocols. Depending on the ratio of $N_{D,w}/N_K$ supplied by a given primary standards laboratory, the observed change at ^{60}Co may become one of the most significant contributing factors to any differences that are observed in high-energy electron beam calibration based on standards of absorbed dose to water.

Column 6 in Table IV represents the product of all the factors that appear in columns 7–11. The small differences observed between the numbers in column 5 and those in column 6 are all accounted for by the differences between $k'_{R_{50}}k_{\text{ecal}}$ values calculated with the factors used in this study and the fitted formula given in the AAPM TG-51 protocol.

V. DETERMINATION OF UNCERTAINTIES

Neither the AAPM TG-21 nor the TG-51 protocols provide an estimation of the uncertainties involved in the process of determination of the absorbed dose to water in reference conditions. In order to determine the uncertainties for the ratio of the absorbed doses determined by the two protocols, a brief analysis of the uncertainties using the $N_X - N_{\text{gas}}$ and $N_{D,w}$ formalisms is presented first. The estimated relative standard uncertainties (u_c) are given in Table VIII and are adapted from the analysis made in the new IAEA Code of Practice,[4] which is based on the ISO guide for the expression of uncertainties,[25] and from Ref. 10. It is assumed that for chambers calibrated at an ADCL, typical standard uncertainties are 0.6% and 0.7% for N_X and $N_{D,w}$, respectively. For the TG-21 $N_X - N_{\text{gas}}$ formalism, the first step made by the user is the determination of the chamber factors N_{gas}. For a cylindrical chamber, the estimated u_c for this factor is 0.9%, which is dominated by an estimated u_c of 0.7% for the denominator of N_{gas}. For a plane-parallel chamber with an N_X calibration factor the estimated u_c is 1.6%, whereas for a chamber cross calibrated by the user in a high-energy electron beam $u_c(N_{\text{gas}})$ is 1.4%. The second step consists of the measurements carried out by the user at the electron beam, and u_c varies with the beam energy and ionization chamber type (see Table VIII). For measurements with a Farmer chamber u_c is around 0.9% and with a plane-parallel chamber 1.1%. The following step corresponds to the user selection of quantities and perturbation factors for the beam-chamber combination. Table VIII, step 3a, gives the most up-to-date estimates available[4] for the factors entering into the $N_X - N_{\text{gas}}$ formalism. The combined standard uncertainty of the product of these factors is about 1% for a Farmer chamber and 0.7% for a plane-parallel chamber. When the three steps are combined, the estimated relative standard uncertainty in the determination of the absorbed dose to water in a high energy electron beam using TG-21 becomes 1.6% for a Farmer chamber, 2.1% for a plane-parallel chamber calibrated in terms of N_X at an ADCL, and 1.9% for a chamber cross calibrated in a high-energy electron beam.

For the first step in the TG-51 $N_{D,w}$ formalism, typical uncertainties for $N_{D,w}^{^{60}\text{Co}}$ calibration factors by ADCLs are around 0.7% for all chamber types and 1.3% for plane-parallel chambers cross calibrated in a high-energy electron beam. Uncertainties associated with the measurements in the user beam, the second step, are identical to those quoted previously for the $N_X - N_{\text{gas}}$ formalism. The only component entering in Table VIII step 3(b) is the uncertainty of the beam quality correction factor k_Q, which for a Farmer chamber is approximately 1.2%, for a plane-parallel chamber is approximately 1.7%, and for a plane-parallel chamber cross calibrated in a high-energy electron beam is 0.6%. When the three steps are combined, the estimated relative standard uncertainty in the determination of the absorbed dose to water in a high energy electron beam using TG-51 becomes approximately 1.6% for a Farmer chamber, and 2.1% and 1.9% for a plane-parallel chamber, the latter value corresponding to the case of a cross calibration.

Two comments should be made at this point. The first is

TABLE VIII. Estimated relative standard uncertainty (%) in the determination of absorbed dose to water at the reference depth in water in high-energy electron beams using the TG-21 $N_X - N_{gas}$ and TG-51 $N_{D,w}$ protocols with cylindrical and plane-parallel ionization chambers.

	TG-21	TG-51	TG-21	TG-51	TG-21	TG-51
Chamber type	Cylindrical calibration from ADCL		Plane-parallel calibration from ADCL		Plane-parallel user cross calibrated in electron beam	
Step 1: User chamber calibration factor	N_{gas}	$N_{D,w}^{^{60}Co}$	N_{gas}	$N_{D,w}^{^{60}Co}$	N_{gas}	$N_{D,w}^{^{60}Co}$
Combined uncertainty	0.9	0.7	1.6	0.7	1.4	1.3
Step 2: User beam measurements						
Long-term stability of user dosimeter	0.3	0.3	0.4	0.4	0.4	0.4
Establishment of reference conditions	0.4	0.4	0.6	0.6	0.6	0.6
Dosimeter reading relative to beam monitor	0.6	0.6	0.6	0.6	0.6	0.6
Correction for T, P, recombination, etc.	0.4	0.4	0.5	0.5	0.5	0.5
Combined uncertainty in user measurements	0.9	0.9	1.1	1.1	1.1	1.1
Step 3a: Quantities and perturbation factors for the user beam						
$(\overline{L}/\rho)_{air}^{w}$	0.5		0.5		0.5	
Assignment of $(\overline{L}/\rho)_{air}^{w}$ to electron beam quality	0.2		0.2		0.2	
P_{gr}	0.3		0.1		0.1	
P_{wall}	0.5		0.3		0.3	
P_{fl}	0.5		0.2		0.2	
P_{cel}	0.1					
W/e (relative to ^{60}Co for high-energy beams)	0.3		0.3		0.3	
Combined uncertainty in quantities and P_i factors	1.0		0.7		0.7	
Step 3b: Beam quality correction. k_Q (calculated) [4]		1.2		1.7		0.6
Combined uncertainty in D_w^Q	1.6	1.6	2.1	2.1	1.9	1.9

that even if the estimated standard uncertainties of the two formalisms appear to be almost identical using updated estimates of the various quantities and factors, the present analysis does not take into account chamber-to-chamber differences in N_{gas} for a given chamber type (other than those included in N_X), which are intrinsically included in $N_{D,w}$ calibrations. To a lesser extent the same occurs with the perturbation factors in calculated k_Q values, which are intrinsically included in measured k_Q values. The second comment refers to the unresolved difference between dose determinations in ^{60}Co using the $N_X - N_{gas}$ and $N_{D,w}$ formalisms, which are most likely related to the primary standards being an aspect beyond the scope of the present work. These issues would undoubtedly increase the uncertainty of the absorbed dose determination for the $N_X - N_{gas}$ formalism but in a manner difficult to estimate at present, favoring the use of a $N_{D,w}$-based protocol.

When independent determinations of absorbed dose to water are made using TG-21 and TG-51, a conservative estimate of the relative standard uncertainty of the dose ratios would simply combine in quadrature the combined uncertainties given in Table VIII for each of the two cases. For the present investigation, however, cancellations must be taken into account, as some of the substeps in step 2 are the same in each of the two cases. Counting step 2 once and combining the uncertainties of steps 1 and 3 in each of the two cases, the estimated combined uncertainty becomes approximately 2.0% for a Farmer chamber and 2.8% for a plane-parallel chamber both calibrated in terms of N_X and $N_{D,w}^{^{60}Co}$, and 2.4% for a plane-parallel chamber cross calibrated in a high-energy electron beam against a calibrated cylindrical chamber.

VI. SUMMARY

Absorbed doses determined with the AAPM TG-51 protocol are found to be higher than those determined with the AAPM TG-21 protocol by 1.0%–3.1% when cylindrical chambers are used in electron beams with energies between 6 and 18 MeV. For plane-parallel chambers the corresponding ratios are found to lie between 1.007 and 1.029 for the direct calibration procedure and between 1.008 and 1.032 for the cross calibration technique.

The reason for the discrepancies between the two protocols has been analyzed. The major factors that contribute to the observed differences between the two protocols are: (i) water-to-air stopping power ratios $(\overline{L}/\rho)_{air}^{w}(I_{max})|_{TG\text{-}21}^{TG\text{-}51}$, (ii) central electrode correction factors $P_{cel}(d_{ref})|_{^{60}Co}^{Q}$, (iii) wall correction factors $P_{wall}(^{60}Co)|_{TG\text{-}51}^{TG\text{-}21}$, (iv) change of standards from N_X to $N_{D,w}^{^{60}Co}$, i.e., $[N_{D,w}^{^{60}Co}(meas)/N_{D,w}^{^{60}Co}(cal)]$, and (v) the differences in the measured values of the absorbed dose to water calibration factors, $N_{D,w}^{cross}$, obtained from cross calibration for plane-parallel chambers. The data and procedures recommended in TG-51 contribute to a maximum difference of 1% in the determination of absorbed dose to water. Another 1.1%–1.2% difference occurs between the two protocols due to the change of standards of air-kerma to standards of absorbed dose to water in ^{60}Co beams.

For cylindrical chamber types the observed differences between the two protocols are within the estimates for combined uncertainty for 6 and 8 MeV when the overall uncertainty in the determination of ratios of absorbed doses between the two protocols is taken into account. However, at higher energies ($10 \leqslant E \leqslant 18$ MeV), the observed differences are larger than the estimated combined uncertainties by about 1%. For plane-parallel chamber types, the observed differences in the ratios of absorbed doses between the two protocols are found to be within the combined estimates for uncertainties for direct calibration technique; for cross-calibration technique the observed differences are found to be within the uncertainty estimates at low energies and comparable at higher energies.

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[1] P. R. Almond, P. J. Biggs, B. M. Coursey, W. F. Hanson, M. Saiful Huq, R. Nath, and D. W. O. Rogers, ''AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams,'' AAPM Task Group 51, Med. Phys. **26**, 1847–1870 (1999).

[2] R. J. Schulz, P. R. Almond, J. R. Cunningham, J. G. Holt, R. Loevinger, N. Suntharalingam, K. A. Wright, R. Nath, and G. D. Lempert, ''A protocol for the determination of absorbed dose from high-energy photon and electron beams,'' AAPM Task Group 21, Med. Phys. **10**, 741–771 (1983).

[3] P. Andreo, J. R. Cunningham, K. Hohlfeld, and H. Svensson, *Absorbed Dose Determination in Photon and Electron Beams: An International Code of Practice*, IAEA Technical Report Series No. 277 (2nd ed. in 1997) (IAEA, Vienna, 1987).

[4] P. Andreo, D. T. Burns, K. Hohlfeld, M. Saiful Huq, T. Kanai, F. Laitano, V. G. Smyth, and S. Vynckier, *Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water*, Technical Report Series No. 398 (IAEA, Vienna, 2000).

[5] Din Deutsches Institut für Normung, *Dosismessverfahren nach der Sondenmethode fur photonen- und elektronenstrahlung, teil 2: Ionisationsdosimetrie, Deutsche Norm DIN 6800-2* (Deutsches Institut für Normung, Berlin, 1997).

[6] IPSM Institute of Physical Sciences in Medicine, ''Code of Practice for high-energy photon therapy dosimetry based on NPL absorbed dose calibration service,'' Phys. Med. Biol. **35**, 1355–1360 (1990).

[7] P. R. Almond, P. Andreo, O. Mattson, A. E. Nahum, and M. Roos, *The Use of Plane-Parallel Ionization Chambers in High-Energy Electron and Photon Beams. An International Code of Practice for Dosimetry*, IAEA Technical Report Series No. 381 (IAEA, Vienna, 1997).

[8] K. R. Shortt, J. Shobe, and S. Domen, ''Comparison of dosimetry calibration factors at the NRCC and the NIST,'' Med. Phys. **27**, 1644–1654 (2000).

[9] G. X. Ding, J. E. Cygler, and C. B. Kwok, ''Clinical reference dosimetry: Comparison between AAPM TG-21 and TG-51 protocols,'' Med. Phys. **27**, 1217–1225 (2000).

[10] M. S. Huq and P. Andreo, ''Reference dosimetry in clinical high-energy photon beams: Comparison of the AAPM TG-51 and AAPM TG-21 dosimetry protocols,'' Med. Phys. **28**, 46–54 (2001).

[11] P. Andreo, ''Absorbed dose beam quality factors for the dosimetry of high-energy photon beams,'' Phys. Med. Biol. **37**, 2189–2211 (1992).

[12] D. W. O. Rogers, ''A new approach to electron beam reference dosimetry,'' Med. Phys. **25**, 310–320 (1998).

[13] A. Kosunen, H. Jarvin, and P. Sipila, ''Optimum calibration of NACP type plane-parallel ionization chambers for absorbed dose determinations in low energy electron beams,'' IAEA-SM-330/cw419 in *Proceedings of the Symposium on Measurement Assurance in Dosimetry*, IAEA, Vienna, 1994, pp. 505–513.

[14] P. R. Almond, F. H. Attix, S. Goetsch, L. J. Humphries, H. Kubo, R. Nath, and D. W. O. Rogers, ''The calibration and use of plane-parallel ionization chambers for dosimetry of electron beams: An extension of the 1983 AAPM protocol, Report of AAPM Radiation Therapy Committee Task Group 39,'' Med. Phys. **21**, 1251–1260 (1994).

[15] D. T. Burns, G. X. Ding, and D. W. O. Rogers, R_{50} as a beam quality specifier for selecting stopping-power ratios and reference depths for electron dosimetry,'' Med. Phys. **23**, 383–388 (1996).

[16] F. M. Khan, K. P. Doppke, K. R. Hogstrom, G. J. Kutcher, R. Nath, S. C. Prasad, J. A. Purdy, M. Rozenfeld, and B. L. Werner, ''Clinical electron-beam dosimetry: Report of AAPM radiation Therapy Committee Task Group No. 25,'' Med. Phys. **18**, 73–109 (1991).

[17] P. Andreo, ''Depth-dose and stopping-power data for monoenergetic electron beams,'' Nucl. Instrum. Methods Phys. Res. B **51**, 107–121 (1990).

[18] C. Malamut, D. W. O. Rogers, and A. F. Bielajew, ''Calculation of water/air stopping-power ratios using EGS4 with explicit treatment of electron-positron differences,'' Med. Phys. **18**, 1222–1228 (1991).

[19] G. X. Ding, D. W. O. Rogers, and T. R. Mackie, ''Calculation of stopping-power ratios using realistic clinical electron beams,'' Med. Phys. **22**, 489–501 (1995).

[20] D. W. O. Rogers and A. Bielajew, ''Differences in electron depth dose curves calculated with EGS and ETRAN and improved energy-range relationships,'' Med. Phys. **13**, 687–694 (1986).

[21] M. Saiful Huq, N. Yue, and N. Suntharalingam, ''Experimental determination of fluence correction factors at depths beyond $d_{\max}$ for a Farmer type cylindrical ionization chamber in clinical electron beams,'' Med. Phys. **24**, 1609–1613 (1997).

[22] P. R. Almond and H. Svensson, ''Ionization chamber dosimetry for photon and electron beams: Theoretical considerations,'' Acta Radiol.: Ther., Phys., Biol. **16**, 177 (1977).

[23] D. W. O. Rogers and C. L. Yang, ''Corrected relationship between %dd(10)x and stopping power ratios,'' Med. Phys. **26**, 538–540 (1999).

[24] G. D. Lempert, R. Nath, and R. J. Schulz, ''Fraction of ionization from electrons arising in the wall of an ionization chamber,'' Med. Phys. **10**, 1–3 (1983).

[25] *ISO International Organization for Standardization 1995 Guide to the Expression of Uncertainty in Measurement*, 2nd ed. (Published by ISO in the name of BIPM, IEC, IFCC, IUPAC, IUPAP and OIML Geneva, ISO).