Calculated absorbed-dose ratios, TG51/TG21, for most widely used cylindrical and parallel-plate ion chambers over a range of photon and electron energies

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Task Group 51 (TG51), of the Radiation Therapy Committee of the American Association of Physicists in Medicine (AAPM), has developed a calibration protocol for high-energy photon and electron therapy beams based on absorbed dose standards. This protocol is intended to replace the air-kerma based protocol developed by an earlier AAPM task group (TG21). Conversion to the newer protocol introduces a change in the determined absorbed dose. In this work, the change in dose is expressed as the ratio of the doses (TG51/TG21) based on the two protocols. Dose is compared at the TG-51 reference depths of 10 cm for photons and d_{ref} for electrons. Dose ratios are presented for a variety of ion chambers over a range of photon and electron energies. The TG51/TG21 dose ratios presented here are based on the dosimetry factors provided by the two protocols and the chamber-specific absorbed dose and exposure calibration factors ($N_{D,w}^{^{60}\mathrm{Co}}$ and N_X) provided by the Accredited Dosimetry Calibration Laboratory (ADCL) at The University of Texas, M. D. Anderson Cancer Center (MDACC). As such, the values presented here represent the expected discrepancies between the two protocols due only to changes in the dosimetry parameters and the differences in chamber-specific dose and air-kerma standards. These values are independent of factors such as measurement uncertainties, setup errors, and inconsistencies arising from the mix of different phantoms and ion chambers for the two protocols. Therefore, these ratios may serve as a guide for institutions performing measurements for the switch from TG21-to-TG51 based calibration. Any significant deviation in the ratio obtained from measurements versus those presented here should prompt a review to identify possible errors and inconsistencies. For all cylindrical chambers included here, the TG51/TG21 dose ratios are the same within $\pm 0.6\%$, irrespective of the make and model of the chamber, for each photon and electron beam included. Photon beams show the TG51/TG21 dose ratios decreasing with energy, whereas electrons exhibit the opposite trend. The dose ratio for photons is near 1.00 at 18 mV increasing to near 1.01 at 4 mV while the dose ratio for electrons is near 1.02 at 20 MeV decreasing only 0.5% to near 1.015 at 6 MeV. For parallel-plate chambers, the situation is complicated by the two possible methods of obtaining calibration factors: through an ADCL or through a cross-comparison with a cylindrical chamber in a high-energy electron beam. For some chambers, the two methods lead to significantly different calibration factors, which in turn lead to significantly different TG51/TG21 results for the same chamber. Data show that if both $N_{D,w}^{^{60}\mathrm{Co}}$ and N_X are obtained from the same source, namely an ADCL or a cross comparison, the TG51/TG21 results for parallel-plate chambers are similar to those for cylindrical chambers. However, an inconsistent set of calibration factors, i.e., using $N_{D,w}^{^{60}\mathrm{Co}} \cdot k_{\mathrm{ecal}}$ from an ADCL but N_{gas} from a cross comparison or vice versa, can introduce an additional uncertainty up to 2.5% in the TG51/TG21 dose ratios.
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Key words: megavoltage, dosimetry, TG51 protocol, TG21 protocol, parallel-plate chambers, cross comparison

I. INTRODUCTION

Since publication of the American Association of Physicists in Medicine (AAPM) absorbed-dose-standard based protocol (TG51[1]) in September 1999, the Radiological Physics Center (RPC) has received numerous phone calls from physicists with questions and concerns or seeking clarifications about the protocol. One important question has been about the difference in the absorbed-dose determined by this protocol compared with TG21.[2,3] This question is being raised more frequently as the switch from the TG21 protocol to the TG51 protocol is gaining momentum. The measured dose-difference between the two protocols, for some selected ion chambers, have been presented in poster presentations[4] and publications.[5–8] Also, calculated differences have been presented for selected chambers in two publications.[6,9] In these studies, a maximum difference of about 2% has been reported for both high-energy photon beams and electron beams. However, differences from 3 to 5%, especially for electron calibrations with parallel-plate ion chambers, have been verbally reported to the RPC by a significant number of

institutions. This work is aimed at responding to this issue. In this work, the difference between dose determined by the two protocols is presented as the ratio of the absorbed dose at a specified reference depth determined using the TG51 protocol to the dose determined using the TG21 protocol at that same depth. In this work, this dose ratio will be referred to as TG51/TG21. The calculated ratios, TG51/TG21, are presented for the most commonly used cylindrical and parallel-plate ion chambers.

These calculations are based on the dosimetry factors from the two protocols and the chamber-model specific average ratio of the absorbed dose calibration factor, $N_{D,w}^{60\mathrm{Co}}$, to the exposure calibration factor, N_X, for the specific chamber. The latter ratio will be identified as $N_{D,w}^{60\mathrm{Co}}/N_X$. With the exception of one chamber, the $N_{D,w}^{60\mathrm{Co}}/N_X$ values used in this work have been obtained from the ADCL located at the University of Texas M. D. Anderson Cancer Center. The TG51/TG21 ratios presented here, therefore, represent the expected change in the dose determined when converting from the one protocol to the other, independent of complication such as measurement uncertainties, setup errors, or inconsistencies caused by the mix of ion chambers, phantoms, calibration depths, and other entities. The only uncertainty included is the uncertainty in the ratio $N_{D,w}^{60\mathrm{Co}}/N_X$ for the users chamber, which is resolved by removing this term from the TG51/TG21 results.

The dose ratios presented in this work are designed to serve as a guide to institutions performing the switch from the TG21 to the TG51 protocol. If an institution determines TG51/TG21 ratios to be measurably different ($>1\%$) than the values presented in this work, that institution should review its calculations for both protocols with regard to the uncertainties, errors, and inconsistencies discussed in this work.

II. MATERIALS AND METHODS

Calculations of the absorbed dose, and therefore dose ratios, presented in this work, are based on equations in the TG51 and TG21 protocols for absorbed dose to water at the same depth, for a specific irradiation time or monitor units. In development of our formalism, the TG51- and TG21-based doses are compared deliberately at the same reference depth "d." This eliminates the need for depth-dose correction factors to transfer the doses to the depth of maximum dose, thereby eliminating uncertainty in the depth-dose factor. The symbolisms of both TG51 and TG21 are used; therefore, redefining the symbols is unnecessary. To minimize uncertainties, the numerical values of M_{raw}, P_{TP}, P_{ion}, and P_{pol}, are assumed to be the same for the two protocols. Although nomenclature is slightly different, M_{raw} and P_{TP} are identical in both protocols. The technique for determining P_{ion} is virtually identical in both protocols. The factors P_{pol} and P_{elec}, which are explicit in TG51, are implicit in TG21. In the following equations, they have been explicitly included for both protocols. Because TG51 is more specific about the reference depth than is TG21, especially for electrons, the TG51 reference depth is chosen. According to TG51 [Eqs. (3) and (8)], absorbed dose "$D_{X,\mathrm{TG51}}$" for photons, at the reference depth, 10 cm, for a given time or monitor set is given by

$$D_{X,\mathrm{TG51}}=(M_{\mathrm{raw}}\cdot P_{\mathrm{TP}}\cdot P_{\mathrm{ion}}\cdot P_{\mathrm{pol}}\cdot P_{\mathrm{elec}})\cdot k_Q\cdot N_{D,w}^{60\mathrm{Co}}. \tag{1}$$

The corresponding dose, $D_{X,\mathrm{TG21}}$, according to TG21 [Eqs. (6), (9), and (10)] is expressed similarly

$$D_{X,\mathrm{TG21}}=(M_{\mathrm{raw}}\cdot P_{\mathrm{TP}}\cdot P_{\mathrm{ion}}\cdot P_{\mathrm{pol}}\cdot P_{\mathrm{elec}})\cdot P_{\mathrm{repl}}\cdot P_{\mathrm{wall}}\cdot L/\rho\cdot N_{\mathrm{gas}}. \tag{2}$$

It should be noted that in both equations, M_{raw} is measured with the center of the cavity of a cylindrical chamber or the front inner surface of the cavity of a parallel-plate chamber placed at the measurement depth "d" without employing any shift to the effective point of measurement. Dividing Eq. (1) by Eq. (2) yields the dose ratio, $D_{x,\mathrm{TG51}}/D_{x,\mathrm{TG21}}$, denoted here as $(\mathrm{TG51/TG21})_x$.

$$(\mathrm{TG51/TG21})_x=\frac{k_Q}{P_{\mathrm{repl}}\cdot P_{\mathrm{wall}}\cdot L/\rho}\cdot\frac{(N_{D,w}^{60\mathrm{Co}}/N_X)}{(N_{\mathrm{gas}}/N_X)}. \tag{3}$$

Because TG51 does not allow parallel-plate chambers for calibration of photon beams, calculation of the dose ratio $(\mathrm{TG51/TG21})_x$ in this work is limited to cylindrical chambers.

For electron beams, the absorbed dose "$D_{e,\mathrm{TG51}}$" at the reference depth measured with a cylindrical chamber is given by

$$D_{e,\mathrm{TG51}}=(M_{\mathrm{raw}}\cdot P_{\mathrm{TP}}\cdot P_{\mathrm{ion}}\cdot P_{\mathrm{pol}}\cdot P_{\mathrm{elec}})\cdot P_{\mathrm{gr}}\cdot N_{D,w}^{60\mathrm{Co}}\cdot k_{\mathrm{ecal}}\cdot k'_{R_{50}}. \tag{4}$$

Here, M_{raw} is the reading with the chamber axis at depth "d." But on closer examination, it is clear that the product $M_{\mathrm{raw}}\cdot P_{\mathrm{gr}}$ is numerically equivalent to the reading M'_{raw}, with the chamber's axis at depth $d'=(d+\mathrm{shift})$. The "shift" is 0.5 times the internal radius "r_{cav}" of the thimble. Therefore, Eq. (4) can be rewritten as

$$D_{e,\mathrm{TG51}}=(M'_{\mathrm{raw}}\cdot P_{\mathrm{TP}}\cdot P_{\mathrm{ion}}\cdot P_{\mathrm{pol}}\cdot P_{\mathrm{elec}})\cdot k'_{R_{50}}\cdot N_{D,w}^{60\mathrm{Co}}\cdot k_{\mathrm{ecal}}. \tag{5}$$

Here, M'_{raw} is the raw reading with the chamber's axis at depth $(d+0.5r_{\mathrm{cav}})$. The corresponding equation for TG21 is

$$D_{e,\mathrm{TG21}}=(M''_{\mathrm{raw}}\cdot P_{\mathrm{TP}}\cdot P_{\mathrm{ion}}\cdot P_{\mathrm{pol}}\cdot P_{\mathrm{elec}})\cdot P_{\mathrm{epl}}\cdot L/\rho\cdot N_X\cdot N_{\mathrm{gas}}/N_X. \tag{6}$$

Here L/ρ and P_{repl} were determined for an incident electron energy, $E_0=2.33\,I_{50}$, where I_{50} is the depth of 50% ionization. M''_{raw} is the raw reading at the calibration depth recommended by the TG21 protocol. TG21 recommends that calibration be performed at ionization maximum, $I_{\max}$, where there is no dose gradient and, therefore, no gradient correction (sic). However, TG21 provides data to calibrate at arbitrary depths. At depths other than $I_{\max}$, a $0.75r_{\mathrm{cav}}$ shift to the effective point of measurement was recommended. How-

TABLE I. Ion chambers and their parameters. In the table, "Poly" stands for Polystyrene, and ID stands for inner diameter.

		Thimble/front window				Collecting electrode				
Ion chamber's Make/Model	Water proof (?)	Material	Thickness (mg/cm^2)	Sensitive volume (cc)	ID or gap (mm)	Material	Diameter/ thickness (mm)	N_{gas}/N_X (cGy/R)	k_{ecal}	$N^{^{60}Co}_{D,w}/N_X$ (cGy/R)
Cylindrical chambers										
NEL 2505-3, -3A	No	Graphite	66.6	0.60	6.3	Aluminum	1.0	0.853	0.903	0.964
NEL 2571	No	Graphite	66.6	0.69	6.3	Aluminum	1.0	0.854	0.903	0.967
NEL 2581	No	Tissue-equivalent	40.0	0.60	6.3	Aluminum	1.0	0.837	0.885	0.966
PTW N30001 (N23333)	No	Acrylic/Graphite	60.3	0.60	6.1	Aluminum	1.0	0.848	0.897	0.965
PTW N30002	No	Graphite	78.6	0.60	6.1	Graphite	1.0	0.854	0.900	0.965
PTW N30004	No	Graphite	78.6	0.60	6.1	Aluminum	1.0	0.854	0.906	0.970
PTW N30006[a]	Yes	Acrylic/Graphite	56.3	0.60	6.1	Aluminum	2.0	0.850	0.897	0.964
PTW N31003 (N233641)	Yes	Acrylic/Graphite	83.0	0.30	5.5	Aluminum	1.5	0.850	0.898	0.968
Capintec PR-O6C	No	Air-equivalent	49.9	0.65	6.4	Air-equivalent	1.6	0.851	0.900	0.963
Capintec PR-O6G	No	Air-equivalent	49.9	0.65	6.4	Air-equivalent	1.6	0.851	0.900	0.964
Exradin A-12	Yes	Air-equivalent	89.0	0.651	6.1	Air-equivalent	1.0	0.866	0.906	0.970
Parallel-plate Chambers										
Holt MPPK	No	Polystyrene	418.0	1.00	2.0	Polystyrene	4.0	0.855	0.900	
Capintec PS-033	No	Mylar[c] (aluminized)	0.5	0.50	2.4	Polystyrene	0.0036	0.884	0.921	
Markus PTW N23343	Yes	Polyethylene[d] (graphitized)	2.3	0.055	2.0	Acrylic	1.03	0.859	0.905	0.992
Roos-type PTW N34001[b]	Yes	Acrylic (graphitized)	118.5	0.35	2.0	Acrylic	1.0	0.852	0.901	0.994
Roos-like Wellh PPC40[b]	Yes	Acrylic (graphitized)	118.5	0.40	2.0	Acrylic	1.0	0.852	0.901	0.992
NACP-02	Yes	Graphite/Mylar	104.0	0.16	2.0	Rexolite	0.6	0.845	0.888	1.000
Exradin P11	Yes	Polystyrene-equivalent	106.0	0.62	2.0	Polystyrene equivalent	1.0	0.848	0.888	0.999

[a]Not included in TG51 (k_Q, k_{ecal}, and $k'_{R_{50}}$ are assumed to be the same as those for PTW N30001).
[b]Not included in TG39 (P_{repl} is assumed to be 1.000).
[c]Polyethylene terephthelete
[d]The manufacturer provides a 0.87 mm thick (103 mg/cm^2) acrylic water-proofing cap.

ever, this was modified by AAPM task group report TG25,[10] which like TG51, recommends a $0.5r_{cav}$ shift. Thus, TG21 calibration at a given depth "d," as modified by TG25, requires positioning of the chamber's axis at depth ($d+0.5r_{cav}$), the same as in TG51 equation (5). This implies that $M''_{raw}=M'_{raw}$. Therefore, dividing Eq. (5) by Eq. (6) leads to the following dose ratio:

$$(\mathrm{TG51/TG21})_e=\frac{k'_{R_{50}}}{P_{repl}\cdot(L/\rho L)}\,\frac{k_{ecal}\cdot(N^{^{60}Co}_{D,w}/N_X)}{(N_{gas}/N_X)}. \qquad (7)$$

Equation (7) holds for parallel-plate chambers as well, because the effective point of measurement, in both protocols, is the inner surface of the front window of the chamber. Equations (3) and (7) were used for calculating the results presented in this work. The various dosimetric parameters were taken from TG51 and TG21. For parallel-plate chambers, the values of P_{repl} were obtained from TG39.[11]

The format of Eqs. (3) and (7) explicitly employ the factor (N_{gas}/N_X) to exploit the use of published values for this ratio.[2,11–13] Because A_{ion} is typically 0.999 or 1.000, N_{gas}/N_X is assumed identical to $N_{gas}/(N_X\cdot A_{ion})$. The values for (N_{gas}/N_X) were taken from Gastorf *et al.*,[12] or calculated from Nath *et al.*[13] using the manufacturer's specifications. The chamber factor ratio, $(N^{^{60}Co}_{D,w}/N_X)$, also appears in the equations. With one exception, $(N^{^{60}Co}_{D,w}/N_X)$ ratios were obtained from the M. D. Anderson Cancer Center ADCL. They represent the measured average over at least three chambers of the same make and model. The standard deviation in these average values is typically better than $\pm 0.2\%$.

III. RESULTS AND DISCUSSION

The relevant characteristics of the 11 cylindrical and 7 parallel-plate ion chambers used for this study are presented in Table I. The characteristics include thimble material and thickness, thimble inner radius and volume, N_{gas}/N_X, the measured calibration factor ratio $N^{^{60}Co}_{D,w}/N_X$, and other variables. The ratios $(\mathrm{TG51/TG21})_x$ and $(\mathrm{TG51/TG21})_e$ were calculated using Eqs. (3) and (7), respectively. The results are presented in Table II and Figs. 1–3. The beam characteristics, specified in various tables and figures, correspond to beams generated from specific linacs, namely a Clinac 4, a Mobetron, and several Clinac 2100s. The beam energy-specifier in Fig. 1 is the ionization ratio, "IR", from TG21; the corresponding specifier for TG51, $\%dd(10)_x$ for the specific beams can be found in Table II. The shaded areas in Figs. 1 and 2 are envelopes of the data, intended to direct the eye to trends with respect to beam energy. The solid curve inside each shaded area represents the average of the trend.

The photon beam results, displayed in Fig. 1, show the dose ratio $(\mathrm{TG51/TG21})_x$, to be highest (1.01) at ^{60}Co, diminishing with increasing beam energy to near 1.00 at 18 MV. All 11 cylindrical chambers included in this study show similar results within tight limits (an envelope of $\pm 0.6\%$) at all energies.

TABLE II. Absorbed-dose ratio TG51/TG21 determined using the two protocols. Energy specifiers and characteristics of each beam are shown at the bottom of the table.

	Photons: Nominal energy (MV)						Electrons: Nominal energy (MeV)					
Ion chamber	Co-60	4	6	10	15	18	4	6	9	12	16	20
Cylindrical												
NEL 2505-3, -3A	1.009	1.006	1.007	1.005	1.004	1.001	1.009	1.014	1.015	1.017	1.018	1.018
NEL 2571	1.010	1.008	1.008	1.006	1.005	1.002	1.010	1.016	1.017	1.018	1.019	1.020
NEL 2581[a]	1.015	1.009	1.010	1.008	1.007	1.003	1.009	1.014	1.015	1.016	1.017	1.018
PTW N30001 (N23333)	1.010	1.006	1.006	1.003	1.003	0.999	1.007	1.013	1.014	1.015	1.017	1.017
PTW N30002	1.008	1.006	1.006	1.003	1.002	0.998	1.003	1.008	1.009	1.011	1.013	1.014
PTW N30004	1.013	1.011	1.012	1.010	1.009	1.006	1.013	1.019	1.020	1.021	1.024	1.025
PTW N30006[b]	1.007	1.003	1.003	1.001	1.000	0.997	1.004	1.010	1.011	1.012	1.014	1.014
PTW N31003 (N233641)	1.010	1.006	1.006	1.004	1.003	1.000	1.008	1.013	1.015	1.016	1.017	1.017
Capintec PR-06C[a]	1.017	1.014	1.011	1.006	1.004	1.000	1.007	1.013	1.014	1.015	1.016	1.016
Capintec PR-06G[a]	1.017	1.014	1.012	1.006	1.005	1.001	1.008	1.013	1.014	1.016	1.017	1.017
Exradin A-12	1.010	1.008	1.006	1.000	0.999	0.996	1.001	1.006	1.007	1.009	1.011	1.012
Parallel plate												
Markus PTWN23343			K_Q for parallel-plate				1.009	1.015	1.017	1.018	1.019	1.019
Roos-type PTW N34001[c]			chambers not included				1.014	1.021	1.022	1.023	1.024	1.024
Roos-like Wellh PPC40[c]			in TG-51				1.012	1.018	1.020	1.021	1.022	1.022
NACP-02							1.013	1.020	1.021	1.022	1.023	1.024
Exradin P11							1.009	1.015	1.016	1.018	1.019	1.019
Beam characteristics												
NAP	2.47	2.86	4.49	8.40	12.52	16.19						
IR	0.572	0.599	0.664	0.729	0.762	0.781						
$\%dd_{(10)X}$ or, I_{50}	58.7[d]	63.6	66.2	73.0	77.0	81.7	1.41	2.34	3.55	4.98	6.53	8.15
R_p							1.91	3.06	4.53	6.27	8.17	10.15
d_{ref}							0.75	1.30	2.05	2.95	3.90	4.90

[a]Labelling is inconsistent in TG51 (Fig. 5). These chambers are assumed to be grouped with NEL 2505-3A.
[b]Not included in TG51. Its values for k_Q, K_{ecal}, and $K'_{R_{50}}$ are assumed to be same as those for PTW N30001.
[c]Not included in TG39. The value of P_{repl} has been assumed to be 1.000.
[d]Value from BJR-25 (value measured on a Theratron 780 unit is 58.3 based on TG51 definition).

Electron results for cylindrical and parallel-plate chambers are presented in Figs. 2 and 3, respectively. Both classes of chambers show that the trend with respect to energy is opposite to that seen for photons. For cylindrical chambers, the dose ratio $(\text{TG51/TG21})_x$ is highest (1.02) at the highest beam energy 20 MeV, and it diminishes with decreasing beam energy to 1.01 at 6 MeV. All 11 cylindrical chambers included in this study again show similar results within tight limits (envelope of $\pm 0.6\%$) over the range of energies. The parallel-plate chambers show results similar to cylindrical

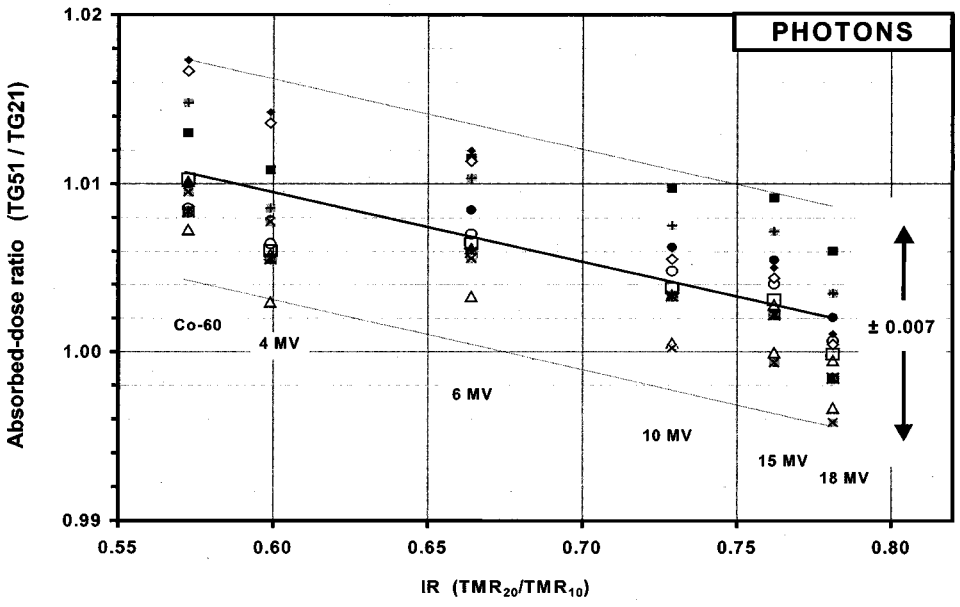

FIG. 1. Photon-beam results for absorbed-dose ratios TG51/TG21. Symbols representing results for various chambers are ○, NEL2505-3 (-3A); ●, NEL2571; +, NEL2581; △, PTW N30001 (N23333); ■, PTW N30004; ▲, PTW N30006; □, PTW N31003 (N233641); ×, Exradin A12; ∗, PTW N30002; ◇, Capintec PR-06C, and ♦, Capintec PR-06G.

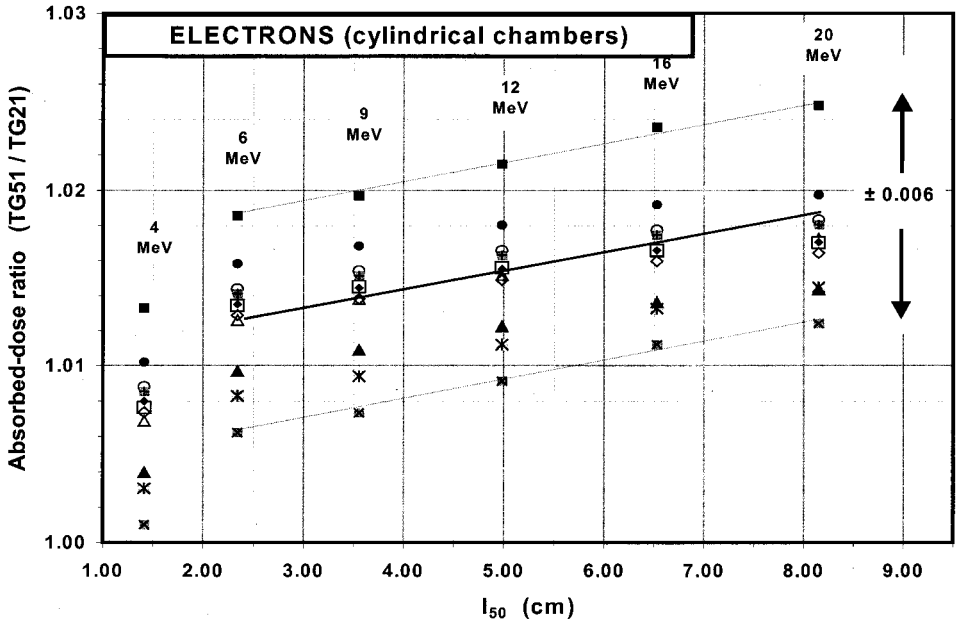

FIG. 2. Electron-beam results for absorbed-dose ratios TG51/TG21 using cylindrical chambers. Symbols representing results for various chambers are ○, NEL2505-3 (-3A); ●, NEL2571; +, NEL2581; △, PTW N30001 (N23333); ∗, PTW N30002; ■, PTW N30004; ▲, PTW N30006; □, PTW N31003 (N233641); ×, Exradin A12; ◇, Capintec PR-06C; and ♦, Capintec PR-06G.

chambers with an even narrower envelope. However, these similar results are only ''apparent'' and are discussed in more detail under ''Parallel-Plate Chambers'' below.

TG51 provides $k'_{R_{50}}$ data only for $R_{50} > 2.0$ cm ($\approx$6 MeV), however, the RPC has received a number of calls asking what to do about electron beams with $R_{50} < 2$ cm. We therefore extrapolated TG51 equations (16), (19), and (20), and Fig. 3 (for the Markus chamber) to determine R_{50} and $k'_{R_{50}}$ in order to calculate results down to 4 MeV electrons ($R_{50} = 1.4$ cm). Validation of our extrapolation of $k'_{R_{50}}$ presented in Sec. V below. The TG51 protocol does not allow the use of cylindrical chambers for energies of 6 MeV or less, so the shading in Fig. 2 was stopped just above 6 MeV. All results are well behaved with a departure from the trend of less than 0.5% at 4 MeV for the cylindrical chambers. This departure is consistent with that seen in the extrapolation discussed in Sec. V.

To this point, all discussion and data show that the conversion from TG21 to TG51 is straightforward and well behaved, and represents only small changes in dose determination. However, there are several issues that can have a significant impact on these results and therefore deserve special attention. These are discussed in items Secs. III A–III G.

A. Parallel-plate chambers

For parallel-plate chambers, ($N^{^{60}\mathrm{Co}}_{D,w} \cdot k_{\mathrm{ecal}}$) and N_{gas} can each be determined in two ways, which we will refer to as

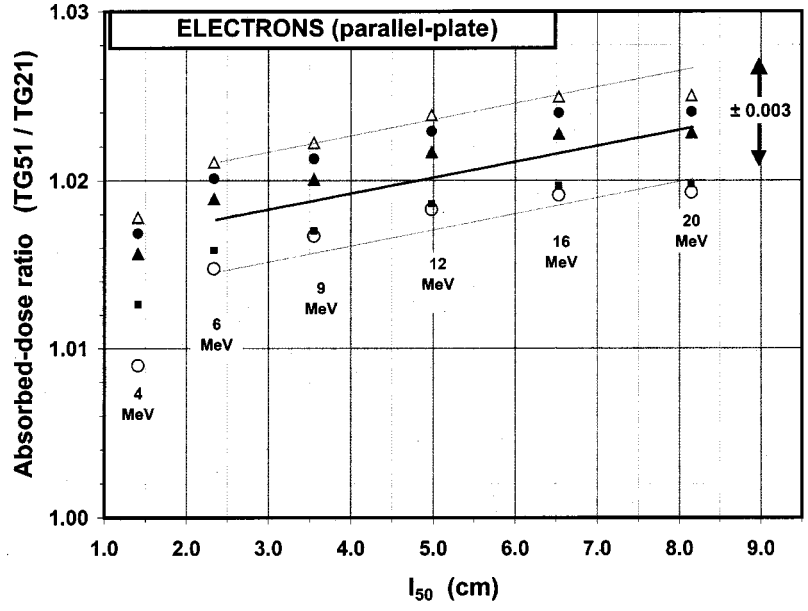

FIG. 3. Electron-beam results for absorbed-dose ratios TG51/TG21 using parallel-plate chambers. Symbols representing results for various chambers are ○, Markus PTW N23343; ■, Exradin P-12; △, Roos type PTW 34001; ▲, Roos-type WellHoffer PPC 35; and ●, NACP-02.

techniques A and B. Following the nomenclature of TG51, in technique B, $N_{D,w}^{^{60}\mathrm{Co}}$ or N_X is obtained from an ADCL, and k_{ecal} or N_{gas}/N_X is obtained from the protocol or literature. In technique A, as recommended by TG51[1] or TG39,[11] the product $(N_{D,w}^{^{60}\mathrm{Co}} \cdot k_{\mathrm{ecal}})$ or N_{gas} is determined by cross comparison with a cylindrical chamber in a high-energy electron beam. For some parallel-plate chambers, the two techniques can give significantly different values. As an illustration, the product $(N_{D,w}^{^{60}\mathrm{Co}} \cdot k_{\mathrm{ecal}})$ for a Markus chamber (model PTW N23343), determined from the ADCL calibration is reported[14] to be more than 2% higher than that determined from the cross-comparison technique. Our own measurements with this chamber yield similar results for N_{gas}. The dual values for $(N_{D,w}^{^{60}\mathrm{Co}} \cdot k_{\mathrm{ecal}})$ and N_{gas} lead to the following four possible combinations and, consequently, four possible dose ratios for TG51/TG21.

(i) Both $(N_{D,w}^{^{60}\mathrm{Co}} \cdot k_{\mathrm{ecal}})$ and N_{gas} are based on an ADCL calibration (technique B).

(ii) Both $(N_{D,w}^{^{60}\mathrm{Co}} \cdot k_{\mathrm{ecal}})$ and N_{gas} are based on a cross comparison (technique A).

(iii) $(N_{D,w}^{^{60}\mathrm{Co}} \cdot k_{\mathrm{ecal}})$ is based on technique B but N_{gas} is based on technique A.

(iv) $(N_{D,w}^{^{60}\mathrm{Co}} \cdot k_{\mathrm{ecal}})$ is based on technique A but N_{gas} is based on technique B.

The TG51/TG21 dose ratios, presented in Table I, are based on the use of combination (i) above. Use of combination (ii) for parallel-plate chambers should yield the same results; however, an inconsistent combination, such as (iii) or (iv), would compromise the presented TG51/TG21 ratios. Continuing with the previous illustration of the Markus chamber, the $(\mathrm{TG51/TG21})_e$ value (1.019) at 20 MeV in Table II, would change by an additional $\pm 2\%$ to 1.04 if combination (iii) was used or 1.00 if combination (iv) was used.

A word of caution is in order. The parallel-plate results based on either combination (i) or (ii) agree with those for cylindrical chambers presented in Table II and Figs. 2 and 3. From this apparent agreement, one should not conclude that the two classes of chambers would necessarily agree in absolute doses as well. In fact, as mentioned above, the Markus chamber is reported to measure approximately 2% higher dose than a cylindrical chamber (Farmer-type NEL 2571 or PTW N30001) at all electron energies, if ADCL factors are used. The TG51 protocol indicates an appreciable uncertainty in the value of k_{ecal} for parallel-plate chambers owing to its high sensitivity to chamber design. In a recent publication by Huq *et al.*,[8] 1.7% correction in the k_{ecal} value for Markus chamber is indicated. As such, the protocol indicates a preference for determining $(N_{D,w}^{^{60}\mathrm{Co}} \cdot k_{\mathrm{ecal}})$ from cross comparison with a cylindrical chamber.

B. Uncertainty in $(N_{D,w}^{^{60}\mathrm{Co}}/N_X)$

The results presented in Table II and Figs. 1–3 are based on the empirical values of $(N_{D,w}^{^{60}\mathrm{Co}}/N_X)$ provided by the M. D. Anderson Cancer Center ADCL. The reproducibility of these values, for a specific make and model of chamber, within one ADCL, is extremely tight ($\sigma < 0.2\%$ at the M. D. Anderson Cancer Center ADCL). However, among various calibration laboratories (NIST, NRCC, and other ADCLs), differences of up to 1% in the values for $N_{D,w}^{^{60}\mathrm{Co}}/N_X$ have been noticed by the RPC. This difference is consistent with respect to the following uncertainty argument. The ADCLs are required[15] by the AAPM to assign a calibration factor within 0.5% of the value assigned by NIST. Assuming that this represents an uncertainty at the 2σ level, we can sum, in quadrature, the uncertainties in the two calibration factors resulting in an uncertainty of $\pm 0.7\%$ for the $N_{D,w}^{^{60}\mathrm{Co}}/N_X$ value. An additional issue concerns the difference between the primary standards maintained by both NIST and NRCC. According to Shortt *et al.*,[16] a difference of $\sim 1.1\%$ exists in the ratio $N_{D,w}/N_X$ from the two standards laboratories. In addition, Cho *et al.*[5] report difference of the order of 1% between a calculated $N_{D,w}^{^{60}\mathrm{Co}}/N_X$ and ADCL supplied values.

C. Refined TG51/TG21 dose ratios

The impact of the uncertainty in $N_{D,w}^{^{60}\mathrm{Co}}/N_X$ on the TG51/TG21 results in Table II is eliminated by removing this factor from Eqs. (3) and (7). The resulting ratios, $(\mathrm{TG51/TG21})/(N_{D,w}^{^{60}\mathrm{Co}}/N_X)$, are presented in Table III. The user, then, can obtain better values for expected (TG51/TG21) dose ratios by multiplying the values shown in Table III by the $(N_{D,w}^{^{60}\mathrm{Co}}/N_X)$ ratio of ADCL calibration factors for their chamber.

D. Comparison with published results

A comprehensive comparison with the published experimental TG51/TG21 results is not presented here because of the uncertainties in $N_{D,w}/N_X$ discussed above. For a limited number of chambers, calculated TG51/TG21 results, and measured results with $N_{D,w}$ and N_X values provided, have been published by Ding *et al.*[6] They present photon results for Co-60, 6 MV, and 18 MV beams using NE2571 and PR-O6C Farmer-type cylindrical chambers. Their electron results use NACP and Markus parallel-plate chambers and the PR-06C cylindrical chamber. Note that their approach, for electrons, is slightly different from ours in that they convert their TG51 dose at d_{ref} to dose at $d_{\max}$, whereas we perform both calibrations at d_{ref}. The comparison therefore reflects differences between L/ρ values from TG21 and those from Burns.[17] Table IV presents a comparison with Ding's NRCC-based TG51/TG21 values after removing the NRCC-based $(N_{D,w}^{^{60}\mathrm{Co}}/N_X)$ factor for their chambers. For the Marcus chamber, the comparison is presented as the direct dose ratio, TG51/TG21, because no $N_{D,w}^{^{60}\mathrm{Co}}$ factor is provided by Ding.

At Co-60 energy, agreement is excellent. For 6 and 18 MV photons, our ratios compared with Ding's for both Farmer-type chambers are 0.3% higher and 0.5% lower, respectively. These minor discrepancies may be attributed to differences in beam quality specifiers. For electron beams, the Markus chamber results agree within 0.3%. For the

TABLE III. Absorbed-dose ratio "TG51/TG21" divided by $(N_{D,w}^{^{60}Co}/N_X)$. Energy specifiers and characteristics of each beam are shown at the bottom of the table. See explanation of superscripts under Table II.

	Photons: Nominal energy (MV)						Electrons: Nominal energy (MeV)					
Ion chamber	Co-60	4	6	10	15	18	4	6	9	12	16	20
Cylindrical												
NEL 2505-3, -3A	1.046	1.044	1.044	1.042	1.041	1.038	1.046	1.052	1.053	1.054	1.056	1.056
NEL 2571	1.045	1.043	1.043	1.041	1.040	1.037	1.045	1.051	1.052	1.053	1.054	1.055
NEL 2581[a]	1.052	1.045	1.047	1.044	1.044	1.040	1.045	1.051	1.052	1.053	1.054	1.055
PTW N30001 (N23333)	1.047	1.043	1.043	1.040	1.040	1.036	1.044	1.050	1.051	1.052	1.054	1.055
PTW N30002	1.045	1.042	1.042	1.039	1.038	1.034	1.039	1.045	1.046	1.048	1.050	1.051
PTW N30004	1.045	1.042	1.043	1.041	1.041	1.038	1.045	1.050	1.052	1.053	1.056	1.057
PTW N30006[b]	1.045	1.040	1.041	1.038	1.037	1.034	1.041	1.047	1.049	1.050	1.051	1.052
PTW N31003 (N233641)	1.044	1.039	1.040	1.037	1.036	1.033	1.041	1.047	1.048	1.049	1.050	1.051
Capintec PR-O6C[a]	1.056	1.052	1.050	1.044	1.043	1.039	1.046	1.052	1.053	1.054	1.055	1.055
Capintec PR-O6G[a]	1.056	1.052	1.050	1.044	1.043	1.039	1.046	1.052	1.053	1.054	1.055	1.055
Exradin A-12	1.040	1.039	1.036	1.031	1.030	1.026	1.032	1.037	1.038	1.040	1.042	1.043
Parallel-plate												
Holt MPPK			k_Q for parallel-plate				1.016	1.022	1.023	1.024	1.025	1.026
Markus PTWN23343			chambers not included				1.017	1.023	1.025	1.027	1.028	1.028
Capintec PSO33			in TG-51				1.010	1.015	1.018	1.021	1.023	1.024
Roos-type PTW N34001[c]							1.020	1.027	1.028	1.029	1.030	1.030
Roos-like Wellh PPC40[c]							1.020	1.027	1.028	1.029	1.030	1.030
NACP-02							1.014	1.020	1.021	1.022	1.023	1.024
Exradin P11							1.010	1.016	1.018	1.019	1.020	1.020
Beam characteristics												
NAP	2.47	2.86	4.49	8.40	12.52	16.19						
IR	0.572	0.599	0.664	0.729	0.762	0.781						
$\%dd_{(10)X}$ or, I_{50}	58.7*	63.6	66.2	73.0	77.0	81.7	1.41	2.34	3.55	4.98	6.53	8.15
R_p							1.91	3.06	4.53	6.27	8.17	10.15
d_{ref}							0.75	1.30	2.05	2.95	3.90	4.90

NACP and the PR-06C chambers, the maximum discrepancy is 1.3%. For the NACP chamber, our results are consistently higher than Ding's by 0.5 to 1.3% whereas for the PR-06C chamber, our results are consistently low from 1.1 to 0.6%. These differences may be attributed to differences in beam quality and the dose calculation at d_{ref} versus $d_{\max}$ as discussed below. The inconsistent labeling of PR-06C for $k'_{R_{50}}$ in Fig. 5 of TG51, as discussed below, may also have contributed to the observed differences.

Our results appear to be in poor agreement (differences up to nearly 2%) with those of Khan.[9] However, Khan includes P_{cel} in his TG21 dose, which we do not. In addition, Khan calculates $N_{D,w}$ from N_{gas}, essentially from N_X, rather than using a measured value. The difference between the two may be up to 1–1 1/2% as shown in our Cobalt 60 results in Table II and in Sang *et al.*[5] Last, Khan compares dose at $d_{\max}$ for electrons, while we compare at d_{ref}. Once these differences are accounted for, we agree to better than 0.5% for the PTW N23333 chamber used by Khan.

E. TG51/TG21 dose ratios for electrons at $d_{\max}$

As indicated earlier, the TG51/TG21 dose ratios presented in Table II, apply at the TG51 calibration depth, d_{ref}. Trans-

TABLE IV. Comparison with the published data by Ding *et al.* (Ref. 6).

		TG51/TG21 for the Markus, and TG51/TG21 divided by the factor $N_{D,w}^{^{60}Co}/N_X$ for others								
					Nominal electron energies (MeV)					
Ion chamber	Source of result	Co-60	6 MV	18 MV	6	8–10	11–12	13–16	17–18	20
NEL2571	Ding *et al.*	1.045	1.039, 1.040	1.041, 1.046						
	This work	1.045	1.043	1.037						
PR-O6C	Ding *et al.*	1.057	1.046, 1.047	1.042, 1.045		1.058–1.060	1.065	1.063	1.064	1.063
	This work	1.056	1.050	1.039		1.053	1.054	1.055		1.055
NACP-02	Ding *et al.*				1.006, 1.008	1.011–1.013	1.013–1.019	1.014–1.019	1.017–1.019	1.020–1.019
	This work				1.020	1.021	1.022	1.023		1.024
Markus	Ding *et al.*				1.006	1.012	1.018	1.019	1.018	1.018
	This work				1.009	1.015	1.017	1.018		1.019

fer of dose from d_{ref} to d_{max} requires the use of the depth-dose factor (ddf) at d_{ref}. There are two potential sets of ddf based on values of L/ρ, from TG21 (TG25) or from Burns *et al.* as recommended in TG51. For our beams, these differences impact only on the 16 and 20 MeV beams. The TG51/TG21 dose ratios at d_{max} will be 0.4% higher than those listed (Table II) at d_{ref} for the high energy beams if L/ρ for TG51 and TG21 protocols are based on Burns and TG21 table, respectively.

F. Sources of uncertainty

Measurable differences in the TG51/TG21 ratios may be introduced by the following.

(i) Measurement at different depths for the two protocols compounds (a) an additional uncertainty in the raw ionization measurement, and (b) any inconsistency in depth-dose data for those depths.

(ii) Use of different P_{ion}, and P_{pol} values for the two protocols.

(iii) Setup uncertainties and machine drift would influence the results if the same undisturbed setup is not used for both protocols.

(iv) Use of different phantom materials for the two protocols.

(v) Use of different ion chambers for the two protocols.

(vi) Use of parallel-plate chambers, where the selection of calibration techniques can introduce uncertainties in excess of 2%, as discussed earlier.

(vii) For photon beams, whether or not one incorporates the ''shift'' in the use of depth-dose factor for transfer of dose from depth of measurement to the depth of dose maximum.

(viii) For electrons, whether the depth-dose factor, used for dose transfer from d_{ref} to d_{max} is based on Burns[17] L/ρ values or the TG21 L/ρ values.

(ix) Inconsistent labeling of two chambers (PR-06C/G and NE2581) in Figs. 5 and 7 of TG51.

(x) Human error in look-up of protocol factors.

G. Assumptions and approximations

Several assumptions and approximations are represented in this work.

(i) Values for k_Q, k_{ecal}, and $k'_{R_{50}}$ for the 0.6-cc waterproof cylindrical chamber, PTW N30006, are not included in TG51. Values were assumed to be the same as for the PTW N30001 (PTW N23333).

(ii) The Roos-type parallel-plate chamber is not included in TG39; however, it was specifically designed to have an adequate guard, so its P_{repl} value was assumed to be 1.000.

(iii) The value of $(N^{^{60}Co}_{D,w}/N_x)$ for the cylindrical chamber PTW N30004 used in this work, was obtained from the University of Wisconsin's ADCL. For all other chambers, the values of $(N^{^{60}Co}_{D,w}/N_x)$ were obtained from the M. D. Anderson Cancer Center ADCL.

(iv) Due to inconsistent labeling of chambers for $k'_{R_{50}}$ in Figs. 5 and 7 of TG51, the NE2581 and PR-06C/G chambers were assumed to be grouped with the NE2505-3A chamber as in Fig. 7.

(v) For $R_{50}<2$ cm, as in case of the 4 MeV electrons, $k'_{R_{50}}$ was obtained by extrapolation of Eqs. (19) and (20) in TG51 for cylindrical and well-guarded parallel-plate chambers, respectively, and the data in Fig. 6 of TG51 for the Markus chamber.

IV. CONCLUSIONS

The values presented for the TG51/TG21 dose ratios in this work are theoretical calculations and therefore free from measurement uncertainties, setup errors, and inconsistencies that are caused by factors such as mix of phantoms, ion chambers, and different depths of measurements. Therefore, measurement of TG51/TG21 yielding a significantly different value (>1%) than listed in this work should prompt a review of measurements and dose calculations for both protocols, with respect to the sources of uncertainties and inconsistencies discussed above.

The better TG51/TG21 values can be obtained using the values provided in Table III multiplied by the $N^{^{60}Co}_{D,w}/N_x$ value for the particular chamber used. The values, so determined, would be free from an ADCL-to-ADCL uncertainty in $N^{^{60}Co}_{D,w}/N_x$. The results for all 11 cylindrical chambers analyzed agree within $\pm 0.5\%$ at each photon and electron energy. The five parallel-plate chambers analyzed exhibit similar ($\pm 0.5\%$) agreement at each electron energy, and show similar values as those for cylindrical chambers. The dose ratio $(TG51/TG21)_e$ for electrons is highest ($\cong 1.02$) for all chambers at the highest beam energy, 20 MeV, and diminishes by nearly 0.5% down to 6 MeV. Photons exhibit an opposite trend, with the $(TG51/TG21)_X$ dose ratio lowest (near 1.00) at the highest beam energy, 18 MV, increasing with decreasing beam energy to near 1.01 at 4 MV.

For parallel-plate chambers, because of the significant difference in the product $N^{^{60}Co}_{D,w} \cdot k_{ecal}$ determined by the two calibration methods seen for some chambers, we emphasize the recommendation in TG51 that ''...when possible, parallel-plate chambers be calibrated against calibrated cylindrical chambers in a high energy electron beam....''

V. VALIDATION FOR EXTRAPOLATION OF $k'_{R_{50}}$ FOR THE 4 MeV ELECTRON BEAM

To validate the extrapolation of $k'_{R_{50}}$ to $R_{50}<2$ cm, the ratio $k'_{R_{50}}$ to $L/\rho \cdot P_{repl}$ was calculated as a function of R_{50} from 6 cm to 1 cm. Since only the parameters L/ρ and P_{repl} in the calculation of $k'_{R_{50}}$ are energy dependent, the ratio $k'_{R_{50}}$ to $L/\rho \cdot P_{repl}$ should be independent of energy for a valid extrapolation. Values of $k'_{R_{50}}$ were based on Eqs. (19) and (20) provided in the TG51 protocol. Values of L/ρ were calculated from Burns[17] best fit expression at d_{ref}, and P_{repl} values were based on TG25.[10] Since Burns expressions were

based on data from machines with R_{50} ranging from 0.98 to 18.6 cm, they should be valid down to 1 cm.

The ratio $k'_{R_{50}}$ to $L/\rho \cdot P_{\text{repl}}$ was plotted as a function of R_{50} for both, a well-guarded parallel-plate chamber and a Farmer-type chamber (inner radius 3.15 mm). For the well-guarded parallel-plate chamber, this ratio is virtually constant over the entire calculated range of R_{50}, while for the Farmer-type chamber, the ratio is constant to better than 0.1% down to approximately $R_{50}=2$ cm, but then begins to diverge by about 0.6% at $R_{50}=1$ cm. This suggests that extrapolation of $k'_{R_{50}}$ equations in TG-51 down to $R_{50}=1$ cm introduces an additional uncertainty of less than 1%.

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