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A modified formalism for electron beam reference dosimetry to improve the accuracy of linac output calibration

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Abstract

Purpose: To present and demonstrate the accuracy of a modified formalism for electron beam reference dosimetry using updated Monte Carlo calculated beam quality conversion factors.

Methods: The proposed, simplified formalism allows the use of cylindrical ionization chambers in all electron beams (even those with low beam energies) and does not require a measured gradient correction factor. Data from a previous publication are used for beam quality conversion factors. The formalism is tested and compared to the present formalism in the AAPM TG-51 protocol with measurements made in Elekta *Precise* electron beams with energies between 4 MeV and 22 MeV and with fields shaped with a 10×10 cm^2 clinical applicator as well as a 20×20 cm^2 clinical applicator in the 18 MeV and 22 MeV beams. A set of six ionization chambers are used for measurements (two cylindical reference-class chambers, two scanning-type chambers and two parallel-plate chambers). Dose per monitor unit is derived using the data and formalism provided in the TG-51 protocol and with the proposed formalism and data and compared to that obtained using ionization chambers calibrated directly against primary standards for absorbed dose in electron beams.

Results: The standard deviation of results using different chambers when TG-51 is followed strictly is on the order of 0.4 % when parallel-plate chambers are cross-calibrated against cylindrical chambers. However, if parallel-plate chambers are directly calibrated in a cobalt-60 beam, the difference between results for these chambers is up to 2.2 %. Using the proposed formalism and either directly calibrated or cross-calibrated parallel-plate chambers gives a standard deviation using different chambers of 0.4 %. The difference between results that use TG-51 and the primary standard measurements are on the order of 0.6 % with a maximum difference in the 4 MeV beam of 2.8 %. Comparing the results obtained with the proposed formalism and the primary standard measurements are on the order of 0.4 % with a maximum difference of 1.0 % in the 4 MeV beam.

Conclusion: The proposed formalism and the use of updated data for beam quality conversion factors improves the consistency of results obtained with different chamber types and improves the accuracy of reference dosimetry measurements. Moreover, it is simpler than the present formalism and will be straightforward to implement clinically.

Keywords: TG-51, Electron beams, Reference dosimetry, Beam quality conversion factors

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I. Introduction

This work investigates the accuracy of a proposed formalism and new data for electron beam reference dosimetry. A review of the current formalism is presented (section I.A.), the new formalism is described (section I.B.) and, finally, the goals of this work are laid out (section I.C.).

I.A. Review of the current formalism

To calibrate the output of electron beams produced by linear accelerators medical physicists follow procedures laid out in reference dosimetry protocols such as the AAPM's TG-51[1] protocol, the IAEA's TRS-398 code of practice[2] and the IPEM's code of practice.[3] These protocols were published in the late 1990s or early 2000s and there have been ongoing efforts to update them based on newly available data. For example, an addendum to the AAPM's TG-51 protocol for reference dosimetry of high-energy photon beams was published in 2014.[4] A wider revision is required for electron beam reference dosimetry.

The AAPM's TG-51 protocol is based on the use of an ionization chamber calibrated in a cobalt-60 reference field. The linac beam is calibrated in terms of absorbed dose to water, D_{w}, which is obtained with

$$D_{\mathrm{w}} = M k_Q N_{\mathrm{D,w}}^{\mathrm{Co}} \tag{1}$$

where M is the fully corrected reading from an ionization chamber with a cobalt-60 calibration coefficient, $N_{\mathrm{D,w}}^{\mathrm{Co}}$, and the beam quality conversion factor, k_Q, is required to convert the cobalt-60 calibration coefficient to that for the beam quality, Q, of interest.

For electron beam reference dosimetry, the TG-51 protocol makes several additional recommendations and requirements that are not needed for photon beam dosimetry. These are:

1. In equation 1, k_Q is factored such that

$$D_{\mathrm{w}} = M P_{\mathrm{gr}}^Q k_{R_{50}} N_{\mathrm{D,w}}^{\mathrm{Co}} = M P_{\mathrm{gr}}^Q k'_{R_{50}} k_{\mathrm{ecal}} N_{\mathrm{D,w}}^{\mathrm{Co}}, \tag{2}$$

where P_{gr}^Q is the gradient correction factor, $k_{R_{50}}$ is the component of k_Q that is independent of gradient effects at the point of measurement (and $k_{R_{50}} = k'_{R_{50}} k_{\mathrm{ecal}}$), $k'_{R_{50}}$ is the electron quality conversion factor and k_{ecal} is the photon-electron conversion factor.

Differing from photon beams, where P_{gr}^{Q} is included in tabulated k_Q factors, a measured P_{gr}^{Q} is required for cylindrical chambers because it is assumed to depend on the ionization gradient and the cavity radius of the chamber. For parallel-plate chambers the gradient correction factor is assumed to be unity because, when positioned with the inside of the front face of the window at the point of measurement, they are assumed to sample the same electron fluence as in water. The parameter $k_{R_{50}}$ is further factored into $k'_{R_{50}}k_{\mathrm{ecal}}$ because the chamber-to-chamber variation of $k'_{R_{50}}$ is much less than that for $k_{R_{50}}$ and k_{ecal} is required for cross-calibrating parallel-plate chambers against cylindrical chambers. The TG-51 protocol also states that k_{ecal} is directly measurable by primary standards labs and, since the publication of TG-51, at least three standards labs have developed this capability.[5–7] It is fixed for a given chamber model (although measurements of k_{ecal} might be subject to chamber-to-chamber variations for chambers of the same type) and is equal to $k_{R_{50}}$ for an electron beam of quality Q_{ecal}. The parameter $k'_{R_{50}}$ is beam quality dependent. Beam quality is specified with the depth at which the absorbed-dose falls to 50 % of the maximum dose, R_{50}.

2. Parallel-plate chambers are recommended to be cross-calibrated against cylindrical chambers in a high-energy electron beam. By cross-calibrating a parallel-plate chamber against a cylindrical chambers one obtains

$$(k_{\mathrm{ecal}}N_{\mathrm{D,w}}^{\mathrm{Co}})^{\mathrm{pp}} = \frac{(MP_{\mathrm{gr}}^{Q}k'_{R_{50}}k_{\mathrm{ecal}}N_{\mathrm{D,w}}^{\mathrm{Co}})^{cyl}}{(Mk'_{R_{50}})^{pp}}. \tag{3}$$

This recommendation, which avoids the need for a calculated (generic) k_{ecal} factor, is based on early evidence[8] that minor construction details significantly affect the response of these chambers in cobalt-60 beams, which would give rise to higher uncertainties in calculations of k_{ecal}. More recent publications[9–14] have demonstrated that for modern parallel-plate chambers (perhaps because of improved manufacturing techniques) this is no longer as much of an issue.

3. A measured gradient correction factor is required for cylindrical chambers. It is determined with

$$P_{\mathrm{gr}} = \frac{M_{\mathrm{raw}}(d_{\mathrm{ref}} + 0.5r_{\mathrm{cav}})}{M_{\mathrm{raw}}(d_{\mathrm{ref}})}, \tag{4}$$

where M_{raw} is the raw ionization chamber reading and r_{cav} is the cavity radius of the ionization chamber. Measurements of ionization chamber response are required at

two depths. Misinterpretation of how the gradient correction factor is measured and applied is one of the most common sources of error made in electron beam reference dosimetry.[15]

4. Parallel-plate chambers are recommended to be used in beams with nominal energy of 10 MeV or less (R_{50} $\leq$4.3 cm) and required to be used in beams with nominal energy of 6 MeV or less (R_{50} $\leq$2.6 cm). This is because of large fluence correction factors for cylindrical chambers in low-energy electron beams that could introduce large uncertainties in $k'_{R_{50}}$ factors from chamber-to-chamber variation in air cavity dimensions. A recent publication[16] has demonstrated that these variations are only at the $\pm$0.4 % level and are on same order as those for parallel-plate chambers.

The evidence from more recent research discussed in 2 and 4 above suggest that the basis for the recommendations and requirements made by TG-51 may be incorrect and should be revisited. In addition, beam quality conversion factors provided in the TG-51 protocol used a semi-analytical approach requiring several correction factors and that required several assumptions. Some of those correction factors are known to have high systematic uncertainties and some of the assumptions required are now known to be incorrect. Although the use of an ionization chamber directly calibrated in MeV electron beams is the best option,[2] it is typically not practical given the extra cost and lack of available calibration services. This is why cobalt-60 calibrations are still required, and therefore, there is a need for more accurate data for beam quality conversion factors.

I.B. Description of a proposed, modified formalism

Recognizing the issues discussed in the previous section, Muir and Rogers[17,18] investigated beam quality conversion factors for electron beams using Monte Carlo simulations with the EGSnrc code system.[19] Their Monte Carlo simulations, which include gradient effects by definition, demonstrated that acceptable results can be obtained for clinical accelerators using cylindrical chambers without the requirement for a measured gradient correction factor. Based on this finding they introduced new notation that is similar to that in TG-51 but using the subscript Q rather than R_{50} to make it clear that gradient effects are implicitly accounted

for (included in the Monte Carlo calculations by definition). Equation 2 then becomes

$$D_{\mathrm{w}} = Mk'_Q k_{\mathrm{Q,ecal}} N^{\mathrm{Co}}_{\mathrm{D,w}}. \tag{5}$$

Where k_Q is still factored, allowing for the use of a modified cross calibration procedure for parallel-plate chambers. This is useful because of stability issues noted previously for parallel-plate chambers,[6,10,13,20,21] which are avoided if cross-calibration against a stable cylindrical chamber is performed at the time reference dosimetry measurements are made. Equation 3 then becomes

$$(k_{\mathrm{Q,ecal}} N^{\mathrm{Co}}_{\mathrm{D,w}})^{\mathrm{pp}} = \frac{(Mk'_Q k_{\mathrm{Q,ecal}} N^{\mathrm{Co}}_{\mathrm{D,w}})^{\mathrm{cyl}}}{(Mk'_Q)^{\mathrm{pp}}}. \tag{6}$$

Although beam quality conversion factors are treated differently in the proposed formalism, the beam quality specifier, R_{50}, remains unchanged.

Muir and Rogers[18] provided data for 10 plane-parallel and 18 cylindrical ionization chamber types - this is the most complete set of accurate beam quality conversion factors for electron beams. Using reasonable assumptions (e.g., that the photon cross-sections used for the simulations, which are based on the same theoretical approach for all low-Z materials, are correlated), systematic uncertainties in these beam quality conversion factors were estimated at the 0.4 % to 0.6 % level. They also compared their results to several other measured[5,22–24] and calculated[25–27] results that were available at the time of that publication and observed very good agreement. Since then other publications have also provided data,[6,7,28] also in good agreement with that of Muir and Rogers.[18]

Muir and McEwen[16] argued that cylindrical chambers could be used for all electron beams, even those with beam energies as low as 4 MeV (the lowest electron beam energy in clinical use). They demonstrated that perturbation correction factors for reference-class cylindrical chambers do not vary by more than ±0.4 %, which is similar to the level of variability observed for parallel-plate chambers.

Given these considerations, a new formalism is proposed (these postulates deliberately follow those from section I.A.):

1. Simplify the formalism as in equation 5 above. The factor k_Q is still factorized into two components, $k_{\mathrm{Q,ecal}}$ and k'_Q, such that a modified cross-calibration procedure (equation 6) can be employed. The main difference with the proposed approach is that a measured gradient correction factor is not required for cylindrical chambers.

2. Parallel-plate chambers can be cross-calibrated against stable cylindrical chambers using equation 6 or they can be used directly if calibrated in a cobalt-60 reference field with equation 5. Caution must be used to ensure their adequate behavior given the issues related to long-term stability noted above.

3. A gradient correction factor is no longer required for cylindrical chambers because it is included, by definition, in Monte Carlo calculations of k_Q. This will save time and might reduce errors in clinical reference dosimetry.

4. Cylindrical reference-class chambers can be used for reference dosimetry measurements in all electron beams. This is an attractive route since the behavior of these chambers is well-established.[4,29] It also simplifies the procedure.

The advantages of this formalism are its simplicity, that it is easy to implement, it is similar to the procedure employed for photon beam calibrations and it uses established, accurate data.

I.C. Goals of this work

The purpose of this work is therefore to investigate the accuracy and consistency of results obtained using the Monte Carlo calculated beam quality conversion factors provided by Muir and Rogers[18] and the proposed formalism summarized above for use in an addendum to TG-51 for electron beam reference dosimetry. This is accomplished by making and comparing measurements analyzed three ways: 1. With the data and formalism from the original TG-51 protocol, 2. With the data presented by Muir and Rogers and formalism presented here; and, 3. With ionization chambers calibrated directly against primary standard for absorbed dose in electron beams as a benchmark for comparison.

II. Method

All measurements are made using electron beams from the National Research Council Canada (NRC) Elekta *Precise* linac in a horizontal geometry incident on a 30×30×30 cm^3 scanning water phantom. This phantom was built in-house and described previously.[30] With

this phantom, we have demonstrated that chambers can be positioned along the beam axis with an uncertainty at the 0.1 mm level.

A calibrated 10 cm mechanical stand-off is positioned against the front window of the phantom to set the initial depth of the chambers along the beam axis at 10.2 cm. This accounts for the thin front window of the phantom, which is scaled for water-equivalence. For parallel-plate chambers, the initial depth is at the outer front face of the chamber and is set by moving the chamber toward the stand-off until the front face just makes contact. For cylindrical chambers, a telescope aligned perpendicular to the phantom is used to set the center of the chamber at the initial depth of 10.2 cm. All measurement depths are then set relative to this reference point.

Depth-ionization measurements are performed with an NACP-02 chamber to obtain R_{50} to determine beam quality conversion factors either from the TG-51 protocol or from Muir and Rogers.[18] The chamber is scanned through the phantom along the beam axis with step sizes between 0.5 mm and 2.5 mm depending on beam energy. The point of measurement of the chamber is shifted by 1.1 mm from the outer front face into the chamber, which is the standard shift used for this chamber at NRC (and is close to the optimal shift of the effective point of measurement determined in other publications[18,31–33]). Charge measurements are integrated at each step for a period of five seconds. Scans are performed with both polarities ($\pm$100 V) and an average of the two scans is taken to account for polarity effects. Ion recombination correction factors are accounted for using parameters from our previous work[13], with the recombination correction factor expressed in terms of the charge liberated in the chamber per linac pulse. The beam quality specifier R_{50} is determined from depth-ionization measurements using the equation given in TG-51, which has been shown to be sufficiently accurate using updated Monte Carlo simulations,[17] rather than converting to a depth-dose curve using water-to-air stopping-power ratios.

The nominal energies of the beams employed and the results for measurements of R_{50} are in table 1 and table 2 along with the beam quality conversion factors required for the analysis described below. Standard clinical applicators are used to shape the field. For all beam energies, the 10×10 cm^2 applicator is employed. Additionally, the 20×20 cm^2 applicator is used for the high-energy (18 MeV and 22 MeV) beams, to investigate the recommendation made in TG-51 that a 20×20 cm^2 field size be used for beams with R_{50} greater than 8.5 cm.

These beams cover the entire clinically relevant energy range.

The reference depth, where chambers are positioned for reference dosimetry measurements, is determined from $d_{\text{ref}} = 0.6R_{50} - 0.1$ cm. Chambers employed are:
Cylindrical Farmer-type - NE2571 and PTW30013. These are used in beams with all energies except 4 MeV - with the horizontal geometry employed it was not possible to position these at the reference depth in the 4 MeV beam.
Cylindrical scanning-type - IBA CC13 and Exradin A1SL. The CC13 was used in beams with all energies. The A1SL was used in a subset of beams (4 MeV and 8 MeV, 18 MeV and 22 MeV but only using the 20×20 cm^2 applicator).
Parallel-plate - Scanditronix NACP-02 and PTW Roos. These are used in beams with all energies.
Cylindrical chambers are positioned with their central axis at d_{ref}. Gradient correction factors, for use with TG-51, are determined with equation 4 by also making measurements after shifting the chamber axis by $0.5r_{\text{cav}}$ downstream from the source. Parallel-plate chambers are positioned with their effective point of measurement (EPOM) at d_{ref}. For the NACP-02, measurements are performed with the EPOM taken to be 1.12 mm (the standard EPOM used at NRC[31] and that recommended by Muir and Rogers[18]) and 0.60 mm (the physical thickness of the front window, which is that recommended by TG-51). For the PTW Roos chamber, the EPOM is taken as 1.26 mm, which is the standard EPOM used at NRC[31] for this chamber and is the same as that used by scaling the front window of the chamber for water equivalence.

The irradiation procedure uses a 10 Gy preirradiation to ensure that the chambers have stabilized followed by a set of at least 5 readings acquired during 200 MU irradiations (≈2 Gy). If it appears that there is a trend to the readings, readings are repeated until no trending is observed. Measurements are made for all chambers at a given energy, with measurements repeated with the first chamber at the end of a set of measurements to investigate linac drift and repeatability of the results. In addition, two field monitor chambers are mounted on the inside of the applicator such that they do not affect the collimated beam at the phantom. These are also used during depth-ionization and reference dosimetry measurements to track any drift in linac output and/or energy (a drift in the ratio of these monitor chamber readings is indicative of a drift in energy and/or beam position drift).

Raw ionization chamber readings, M_{raw}, are corrected using

$$M = M_{\text{raw}} P_{\text{TP}} P_{\text{ion}} P_{\text{pol}} P_{\text{elec}} P_{\text{leak}} P_{\text{rp}} \tag{7}$$

where:

P_{TP} is the correction to standard environmental conditions of temperature and pressure. It is obtained with the equation given in TG-51.

P_{ion} is the ion recombination correction factor. It is obtained using the ion recombination correction factors parameterized as a function of dose-per-pulse as in previous work[13,29] where a comparison was also made to other publications.

P_{pol} is the correction for polarity effects. It is obtained by taking measurements using voltages of opposite polarities with each chamber for each energy. Preirradiation of the chambers is performed each time the polarizing voltage is changed before taking measurements.

P_{elec} is the electrometer correction factor. It was measured at the time the electrometers used for this work were calibrated traceable to primary electrical standards (via a calibrated voltage source and calibrated capacitors).

P_{leak} is the leakage correction factor. After irradiation, leakage current is collected for at least the amount of time required for irradiation. In this work, leakage always contributes to less than 0.05 % of the signal acquired during irradation so no correction for leakage is applied.

P_{rp} is the radial profile correction factor introduced by the addendum to TG-51 for photon beams[4] to correct for beam non-uniformity over the chambers' central volume. It is acquired using high-resolution 2-dimensional scans with a PTW microDiamond over the region covering the chambers' active volume. For all chambers and all beam energies the correction for beam non-uniformity is less than 0.15 %. The application of this correction factor here is potentially confusing because it accounts for variation of the properties of the electron beam unlike the other corrections that account for the non-ideal behavior of the ionization chamber. It is kept in equation 7 to maintain consistency with the addendum to TG-51 for MV photon beams.[4]

With these measurements, we derive dose per monitor unit (D/MU) three ways:

1. The TG-51 protocol for electron beam reference dosimetry is followed strictly (see section I.A.), except that the updated k_{ecal} factor for the NACP-02 chamber from

Mainegra-Hing et al.[34] is used here because data are not available in TG-51 for this chamber type. This approach uses the formalism of TG-51 (equation 2), the data for k_{ecal} and $k'_{R_{50}}$ from TG-51, a measured gradient correction factor for cylindrical chambers (equation 4) and cross-calibration of parallel-plate chambers is performed against cylindrical chambers in 18 MeV and 22 MeV beams. Data for $k'_{R_{50}}$ for Farmer-type chambers and parallel-plate chambers use the fits given in TG-51 (equations 19 and 20 in that report). For the 4 MeV beam, the fit to $k'_{R_{50}}$ for parallel-plate chambers is still used to extrapolate to R_{50} =1.81 cm even though the fit is only valid to R_{50} =2 cm; this is the only way that data can be obtained from TG-51 for this low-energy beam. The difference in $k'_{R_{50}}$ for R_{50} =1.81 cm and R_{50} =2 cm is only 0.3 % so the use of this extrapolation will not significantly impact the results. Data for the scanning-type chambers are extracted from figure 5 in TG-51 for the chambers that are most similar to the IBA CC13 and Exradin A1SL, which are the Wellhofer IC-10 and Exradin A1, respectively. The beam quality conversion factors used for this method of analysis are provided in table 1. Parallel-plate chambers are used both ways allowed in TG-51 in all beam energies (directly calibrated in cobalt-60 and the preferred method where they are cross-calibrated in high-energy beams). Cylindrical chambers (directly calibrated in cobalt-60) are used for all beams except the 4 MeV beam since this is not allowed by TG-51.

2. The formalism laid out in section I.B. is followed. Cylindrical chambers are positioned with the chamber axis at the reference depth and no gradient correction factor is applied because they are implicitly included in Monte Carlo calculations of beam quality conversion factors. Parallel-plate chambers are used in all beams either directly using a cobalt-60 calibration or with the modified cross-calibration procedure described above. The data from Muir and Rogers[18] are used, extracted from the tables in that work for $k_{\text{Q,ecal}}$ and using the fits given in that work to determine k'_Q with the measured values of R_{50}. The beam quality conversion factors used for this method of analysis are provided in table 2. Data for all chambers employed here are provided in that work. Extrapolation is not required for the 4 MeV beam since Muir and Rogers included beams with R_{50} as low as 1.69 cm.

Although it is tempting to also perform the analysis with updated $k'_{R_{50}}$ values and using a measured gradient correction factor for cylindrical chambers, it is difficult because one

must extract the gradient correction factor from the Monte Carlo calculated k'_Q factors, which include gradient effects by definition. Muir and Rogers[17] showed that there is unacceptable scatter (RMSD=0.38 %) in the resulting $k'_{R_{50}}$ factors when the shift of $0.5r_{\text{cav}}$ is used to determine and extract the gradient correction factor. The same is true when a shift of $0.5r_{\text{cav}}$ of the chamber axis by $0.5r_{\text{cav}}$ downstream from the source, as required by the IAEA TRS-398,[2] is employed. Muir and Rogers[17] showed that when considering results for clinical beams and including gradient effects by definition, the scatter of k'_Q as a function of R_{50} is acceptable (RMSD=0.15 %), indicating that, although the gradient correction factor can potentially vary from machine to machine, including it for clinical beams in Monte Carlo calculated k'_Q factors yields acceptable results.

3. Chambers calibrated directly against NRC primary standards for absorbed dose in electron beams are used to obtain dose with

$$D_{\text{w}} = MN^{\text{Q}}_{\text{D,w}}, \tag{8}$$

where $N^{\text{Q}}_{\text{D,w}}$ is the calibration coefficient for the chamber in the beam of interest. NRC primary standards for absorbed dose are described elsewhere[6,22] and are in good agreement with other primary standards dosimetry laboratories.[7,35] Three of the chambers used in this investigation (the NACP-02, the PTW Roos and the NE2571) have been calibrated directly against NRC primary standards. This method is considered to be the benchmark in this work for comparing the first two methods.

The reference for comparison is the result from the electron beam primary standard and so the difference from this value, along with consistency between chambers, that is of interest.

III. Results

The main results of this work are in figures 1 and 2. Figure 1 (a) shows an average of results for dose per monitor unit obtained using different chamber types using the recommendations of TG-51. Results obtained using the two methods allowed by TG-51 are shown. The results labelled "cross-calibration" use the methods recommended by TG-51. In this case, parallel-plate chambers are cross-calibrated against cylindrical chambers in the 22 MeV beams (more

details on the results for $(k_{\text{ecal}} N_{\text{D,w}}^{\text{Co}})^{\text{pp}}$ are discussed below). For the 4 MeV beam, only results using parallel-plate chambers are considered. For the 8 MeV and 12 MeV beams, results obtained with all chambers are considered using cylindrical chambers calibrated in cobalt-60 and cross-calibrated parallel-plate chambers. For the 18 MeV and 22 MeV beams, only results obtained with cylindrical chambers are considered (since a cross-calibrated parallel-plate chamber would produce redundant results). The results labelled "direct" use the other approach allowed, but not recommended by TG-51, where all chambers are calibrated directly in cobalt-60. Again, for the 4 MeV beam, only the results obtained with the two parallel-plate chambers are considered. The error bars demonstrate the variability of results obtained using different chambers rather than the conventional method of conveying uncertainties. This is done to provide a concise visual demonstration of the consistency (or lack thereof) of results obtained using different chamber types. For the 4 MeV beam, the error bars reflect the difference in results obtained using the two parallel-plate chambers; since there are only two results the difference between them is relevant rather than the standard deviation. For all other points, the error bars are the standard deviation of results using different chambers. The results labelled "NRC" use chambers calibrated directly against NRC primary standards for electron beam dosimetry. Figure 1 (b) shows an average of results for dose per monitor unit obtained using different chamber types using the formalism proposed in this work. In this case, the points labelled "cross-calibration" are an average of results for plane-parallel chambers cross-calibrated against cylindrical chambers in high-energy beams using the modified cross-calibration procedure described above and directly calibrated cylindrical chambers. The points labelled "direct" use results obtained using all chambers directly calibrated in cobalt-60. The error bars on all points reflect the variability of the results obtained using different chamber types and in all cases are the standard deviation of the results.

Figure 2 is the same as figure 1, except that the results are obtained in the 18 MeV and 22 MeV beams shaped with the 20×20 cm^2 applicator. For figure 2 (a), all results use chambers calibrated directly in cobalt-60. Results are shown for only cylindrical chambers (as is implied to be recommended by TG-51) or with all chambers (including directly calibrated parallel plate chambers). Figure 2 (b) shows results obtained for all chambers using the proposed method. Again, in both plots the results are compared to chambers calibrated directly against primary standard for absorbed dose and the error bars are the standard

deviation of results obtained using different chamber types and so reflect the variability or consistency results among chambers.

Although it is not shown in figures 1 or 2, except for the 4 MeV beam following the TG-51 approach (because only the results for the two parallel-plate chambers are applicable), the difference between the maximum and minimum values for D/MU using different chamber types is approximately 1 % following TG-51 recommendations (using cross-calibrated parallel-plate chambers for low-energy beams and using only cylindrical chambers for high-energy beams) and 2 % using all chambers directly calibrated in cobalt-60. The difference in the maximum and minimum values for D/MU using different chamber types following the proposed approach with updated data is approximately 1 % using either chambers directly calibrated in cobalt-60 or when parallel-plate chambers are cross-calibrated and used in low-energy beams.

Table 3 compares the results using the different methods described in this work compared to those obtained using NRC reference-class chambers directly calibrated against NRC primary standards in electron beams. This comparison uses the same results as in figures 1 and 2 described above.

In the above, when cross-calibration is performed for parallel-plate chambers and then used to derive D/MU, the value of $(k_{\text{ecal}}N^{\text{Co}}_{\text{D,w}})^{\text{pp}}$ uses results obtained in the 22 MeV with the 20×20 cm^2 applicator. Cross-calibration is against the reference NE2571 Farmer-type chamber. Comparing results obtained in any of the other high-energy beams (18 MeV or 22 MeV, 10×10 cm^2 applicator or 20×20 cm^2 applicator) using the same method (TG-51 or proposed) gives results that are consistent within 0.2 %. However, table 4 shows that the different methods produce different results for $(k_{\text{ecal}}N^{\text{Co}}_{\text{D,w}})^{\text{pp}}$. The three values in table 4 for the NACP-02 chamber obtained with the proposed formalism and either cross-calibration or direct calibration and using primary standard for absorbed dose are identical, which seems strange but is coincidental (the results in the table are identical from rounding to three decimal digits, not a transcription error).

For this work, all chambers were calibrated in a cobalt-60 reference field within a few weeks of the electron beam measurements. The cobalt-60 calibration coefficients for the two Farmer-type chambers are in excellent agreement within 0.1 % compared to their historical values. This is not surprising as these are laboratory-maintained reference-class chambers

that are regularly monitored and known to be stable. The two scanning type chambers have very little calibration history in cobalt-60. The A1SL has been calibrated twice previously, once in 2008 and once in 2014. These results (obtained in January 2019) are within 0.2 % and 0.35 % of the values obtained in 2014 and 2008, respectively. Although these drifts are larger than usually seen for Farmer-type chambers, this level of agreement is consistent with the specifications for a reference-class chamber.[4] Similarly, the CC13 calibration coefficient was only calibrated once previously in 2008. The value obtained for this work is within 0.4 % of that historical value. The parallel-plate chambers exhibited slightly worse stability than the scanning type chambers. For the PTW Roos, the value obtained in January 2019 was 0.3 % and 0.6 % different from results obtained in 2011 and 2010, respectively. Similarly, for the NACP-02, these results are 0.6 % and 0.7 % different from results obtained in 2011 and 2010, respectively. The stability of these parallel-plate chambers has also been monitored in electron beams in the intervening years with a level of stability at about the 0.25 % level. This level of stability is consistent with the results observed by Bass et al.[21] for a large sample of chambers.

IV. Discussion

Figure 1 (a) shows that the standard deviation of results using different chambers when TG-51 is followed strictly is on the order of 0.4 % when parallel-plate chambers are cross-calibrated against cylindrical chambers. This is the approach recommended in TG-51 and clearly produces more consistent results using parallel-plate chambers. In the 4 MeV beams, the difference between the two parallel-plate chambers is only 0.25 %. If, however, parallel-plate chambers are directly calibrated in a cobalt-60 beam (which is allowed by TG-51 but not recommended), the difference between results for these chambers is up to 2.2 % in the 4 MeV beam. This is caused by the large difference between $(k_{\mathrm{ecal}} N_{\mathrm{D,w}}^{\mathrm{Co}})^{\mathrm{pp}}$ for the PTW Roos chamber (see table 4). This difference is also the reason why the standard deviation of results is larger for all other points when direct calibration is employed. The same situation is apparent in figure 2 (a). Table 3 shows that the difference between results that follow TG-51 and those obtained with chambers calibrated directly against primary standard measurements are on the order of 0.6 % except for the 4 MeV beam where the difference is 2.8 %.

Figure 1 (b) shows that when the proposed formalism and updated data are used standard deviation using different chambers is on the order of 0.4 %, similar to that in figure 1 (a) when cross-calibration is employed. The results and standard deviation are very similar when parallel-plate chambers are directly calibrated in cobalt-60 or cross-calibrated against cylindrical chambers in the 22 MeV beam. Table 3 shows that the agreement between these results and those obtained with chambers calibrated directly against primary standards for absorbed dose are on the order of 0.4 % with a maximum difference of 1.0 % in the 4 MeV beam. This level of agreement is slightly better than when TG-51 is followed for higher energy beams but using the proposed approach really improves the comparison in the lowest energy (4 MeV) beam. Figure 2 (b) shows a similar level of consistenty (standard deviation≈0.4 %) among results obtained using different chamber types when the 20×20 cm^2 applicator is used. Figure 2 and table 3 demonstrate excellent agreement using the proposed method compared to results obtained with chambers calibrated directly against primary standard measurements in high-energy beams shaped with the 20×20 cm^2 applicator, better than that when TG-51 is followed.

Table 4 shows that there is better agreement between $(k_{\text{ecal}}N_{\text{D,w}}^{\text{Co}})^{\text{pp}}$ with the primary standard measurements when the direct approach, not recommended in TG-51, is used compared to the values obtained when the cross-calibration procedure is employed for the PTW Roos chamber. This improvement is likely only fortuitous but explains the better agreement with primary standard measurements observed in table 3 with the direct approach, especially for the 4 MeV beam where only the IBA NACP-02 and PTW Roos chambers can be used following TG-51.

Table 4 demonstrates better consistency compared to the use of TG-51 between $(k_{\text{ecal}}N_{\text{D,w}}^{\text{Co}})^{\text{pp}}$ results obtained using the proposed method if parallel-plate chambers are cross-calibrated or used directly. It also shows that they are in better agreement with those obtained with primary standard measurements. This suggests a higher level of accuracy for results obtained using the proposed formalism.

There is some difficulty drawing conclusions about the consistency of results obtained using different chamber types when data for beam quality conversion factors from TG-51 are used to derive D/MU because TG-51 calculations of beam quality conversion factors for chambers of the same type used the same assumptions and much of the same data for

individual correction factors. Therefore, the consistency between results might be misleading. Conversely, the results for beam quality conversion factors used in the proposed formalism are from independent Monte Carlo calculations using different geometrical chamber models and materials. So although there are some correlations (e.g., the use of the same Monte Carlo code system for all calculations) the results obtained using different chambers with the proposed formalism are more independent than those that use data from the TG-51 protocol. Therefore, the level of consistency obtained using the proposed formalism is not fortuitous.

The 5 % difference observed in figures 1 and 2 between the results for D/MU obtained with the 10×10 cm^2 applicator and the 20×20 cm^2 applicator was investigated with follow-on Monte Carlo simulations using BEAMnrc. The increased dose for the 10×10 cm^2 field size is caused by electrons scattering from the photon jaws and applicator that contribute to dose at the reference depth. That R_{50} is only slightly impacted on the order of 1 mm by this effect indicates that the magnitude of the effect is similar at d_{max} and at deeper depths (i.e., R_{50}).

There is very little difference in the consistency and accuracy of any of the results obtained using the 20×20 cm^2 field size or in R_{50} (see table 1) compared to using the 10×10 cm^2 field size. This observation suggests that a revised protocol can also be simplified by making all reference dosimetry measurements with a 10×10 cm^2 field size.

These results point to questionable stability of parallel-plate chambers and this was also noted in previous publications.[6,13,20,21,36]. This behavior implies that a method of stability monitoring is required if parallel-plate chambers are to be used with a direct cobalt-60 calibration or that they be cross-calibrated against stable cylindrical chambers at the time reference dosimetry measurements are made. Of course, best practice (and a requirement in TG-51) is that secondary checks of reference dosimetry equipment be made for all chambers.

Although there is limited improvement in terms of accuracy in results obtained using the proposed formalism over those obtained with TG-51, there are practical improvements using the new approach. A simplified procedure has advantages in terms of robustness, can help reduce clinical workload and reduce errors in the clinic. In addition, allowing the use of more chamber types in all electron beams (i.e., reference-class cylindrical chambers that have well-established behavior in photon beams) opens up the possibility for making

reference dosimetry measurements with more redundant systems. We intend to test the proposed formalism in clinical settings in the near future to get feedback from multiple users.

V. Conclusions

A formalism is presented that is simplified compared to the AAPM TG-51 used by clinical medical physicists in North America. It allows the use of calibrated cylindrical ionization chambers in all electron beams (even those with low beam energies) and does not require a measured gradient correction factor. In addition, more accurate data for beam quality conversion factors are available for use with an updated formalism. The proposed formalism is tested and compared to the present formalism and using data available in the AAPM TG-51 protocol. The results also indicate that all electron beam reference dosimetry measurements can be made in a 10×10 cm^2 field, which would simplify the calibration procedure and eliminate the need for multiple set-ups.

The use of the proposed formalism and updated data for beam quality conversion factors improves the consistency of results obtained with different chamber types and improves the accuracy of reference dosimetry measurements.

It is conceivable that a simplified formalism for reference dosimetry will reduce clinical workload and reduce errors in reference dosimetry measurements due to misinterpretation. In addition, allowing the use of more chamber types (i.e., cylindrical reference-class chambers) introduces the potential for more redundant systems.

VI. Acknowledgements

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VII. Disclosure of Conflicts of Interest

The author has no conflicts of interest to disclose.

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VIII. Figures and tables

Table 1: The nominal energies of the electron beams and beam quality specifiers (the depth where the absorbed dose falls to 50 % of its maximum value, R_{50}), used in this work. The beam quality conversion factors used to follow the TG-51 approach, as described in the text, are provided for each chamber type.

Beam		$k'_{R_{50}}$					
Nominal energy (MeV)	R_{50} (cm)	NE2571	30013	CC13	A1SL	NACP-02	Roos
10×10 cm^2 applicator							
4	1.81	-	-	-	-	1.059	1.059
8	3.23	1.020	1.020	1.018	1.024	1.038	1.038
12	4.71	1.010	1.010	1.009	-	1.022	1.022
18	7.05	1.001	1.001	1.001	-	1.004	1.004
22	8.69	0.997	0.997	0.996	-	0.994	0.994
20×20 cm^2 applicator							
18	7.10	1.001	1.001	1.001	1.002	1.003	1.003
22	8.80	0.997	0.997	0.996	0.995	0.993	0.993
		k_{ecal}					
Q_{ecal}	7.50	0.903	0.897	0.904	0.915	0.885	0.901

Table 2: The nominal energies of the electron beams and beam quality specifiers (the depth where the absorbed dose falls to 50 % of its maximum value, R_{50}), used in this work. The beam quality conversion factors used to follow the updated approach, as described in the text, are provided for each chamber type.

Beam		k'_Q					
Nominal energy (MeV)	R_{50} (cm)	NE2571	30013	CC13	A1SL	NACP-02	Roos
10×10 cm^2 applicator							
4	1.81	-	-	1.036	1.041	1.064	1.064
8	3.23	1.023	1.022	1.020	1.024	1.037	1.037
12	4.71	1.011	1.010	1.010	1.018	1.019	
18	7.05	1.002	1.002	1.001	-	1.002	1.002
22	8.69	0.998	0.998	0.997	-	0.995	0.995
20×20 cm^2 applicator							
18	7.10	1.002	1.001	1.001	1.001	1.002	1.002
22	8.80	0.998	0.998	0.997	0.995	0.995	0.995
		$k_{\text{Q,ecal}}$					
Q_{ecal}	7.50	0.903	0.901	0.904	0.914	0.892	0.898

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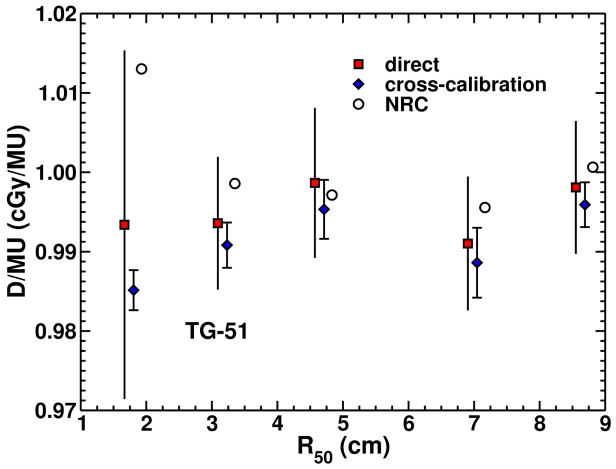
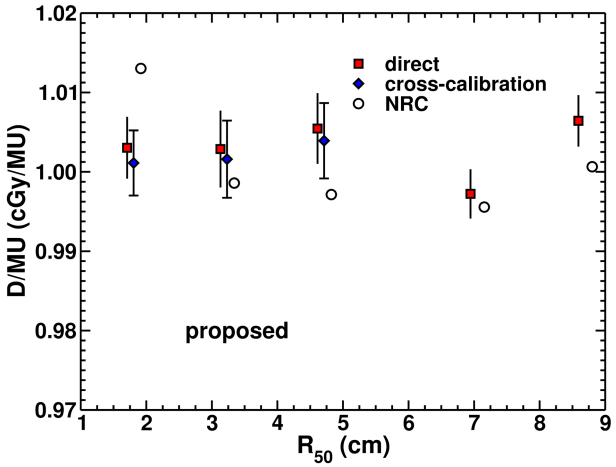


(a)



(b)

Figure 1: The results for dose/MU determined using different methods using the 10×10 cm^2 applicator as a function of R_{50}. The data are offset slightly along the x-axis for clarity. The errors bars are the standard deviation of results obtained using different chambers. For the lowest energy points in panel (a), the error bars reflect the difference between the results obtained using the two parallel-plate chambers. Panel (a) uses the approaches in TG-51 while panel (b) uses the formalism and data proposed in this work. More details on the different methods are described in the text. The same scale is used on both plots to make it easier to compare results. The data labelled "NRC" in both plots are identical.

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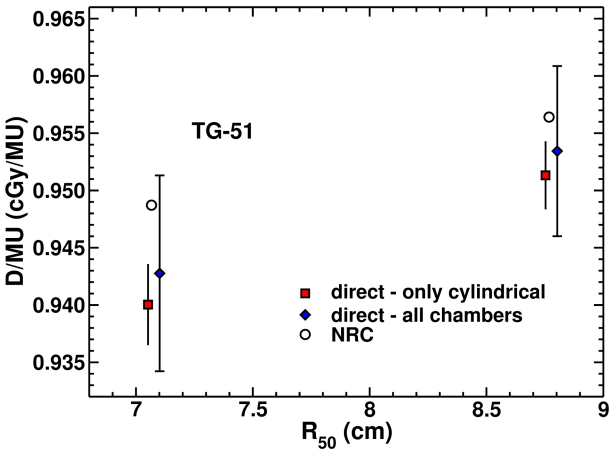
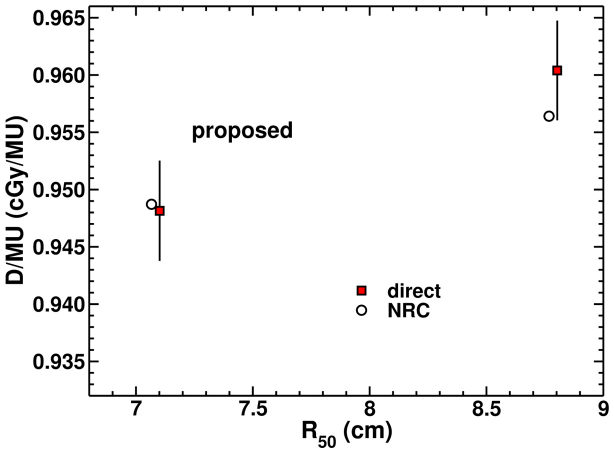


(a)



(b)

Figure 2: As in figure 1 but using the 20×20 cm^2 applicator. These results are for the 18 MeV and 22 MeV beams.

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Table 3: Comparison of different methods to determine absorbed dose. The comparison is against method 3, where chambers are calibrated directly against primary standards for absorbed dose. The percent differences (given in columns 2, 3 and 4) are calculated as $\Delta = \frac{x_{\mathrm{NRC}} - x_{method}}{x_{\mathrm{NRC}}}$.

Nominal energy (MeV)	TG-51 recommended (%)	TG-51 direct (%)	Proposed direct (%)
	10×10 cm^2 applicator		
4	2.75	1.94	0.99
8	0.78	0.50	-0.43
12	0.18	-0.15	-0.83
18	0.70	0.46	-0.17
22	0.47	0.26	-0.58
	20×20 cm^2 applicator		
18	0.91	0.63	0.06
22	0.53	0.31	-0.42

Table 4: Comparison of different methods of obtaining the parameter, $(k_{\mathrm{ecal}} N_{\mathrm{D,w}}^{\mathrm{Co}})^{\mathrm{pp}}$. The percent differences are calculated as $\Delta = \frac{x_{\mathrm{NRC}} - x_{method}}{x_{\mathrm{NRC}}}$.

	PTW Roos		NACP-02	
Method	$(k_{\mathrm{ecal}} N_{\mathrm{D,w}}^{\mathrm{Co}})^{\mathrm{pp}}$	Δ (%)	$(k_{\mathrm{ecal}} N_{\mathrm{D,w}}^{\mathrm{Co}})^{\mathrm{pp}}$	Δ (%)
TG-51 cross-calibration	7.555	1.35	15.686	0.64
TG-51 direct	7.692	-0.45	15.664	0.78
Proposed cross-calibration	7.608	0.65	15.788	0.00
Proposed direct	7.667	-0.11	15.788	0.00
NRC direct	7.658		15.788	

IX. Figure captions

Figure 1: The results for dose/MU determined using different methods using the 10×10 cm^2 applicator as a function of R_{50}. The data are offset slightly along the x-axis for clarity. The errors bars are the standard deviation of results obtained using different chambers. For the lowest energy points in panel (a), the error bars reflect the difference between the results obtained using the two parallel-plate chambers. Panel (a) uses the approaches in TG-51 while panel (b) uses the formalism and data proposed in this work. More details on the different methods are described in the text. The same scale is used on both plots to make it easier to compare results. The data labelled "NRC" in both plots are identical.

Figure 2: As in figure 1 but using the 20×20 cm^2 applicator. These results are for the 18 MeV and 22 MeV beams.