A new approach to electron-beam reference dosimetry

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A new approach is proposed for electron-beam dosimetry under reference conditions and data necessary to use this approach are presented. The approach has the following features: it uses ion chambers and starts from an absorbed-dose calibration factor for ^{60}Co to be consistent with the present proposal for the new AAPM photon-beam protocol; it uses R_{50} to specify the beam quality and the reference depth, $d_{\mathrm{ref}}=0.6R_{50}-0.1$ (all quantities in cm), recommended by Burns *et al.* [Med. Phys. **23**, 383–388 (1996)]; it has a formalism which is parallel to the k_{Q} formalism for photon-beam dosimetry; it fully accounts for the impact on stopping-power ratios of realistic electron beams; it allows an easy transition to using primary standards for absorbed dose to water in electron beams when these are available. The equation for dose to water under reference conditions is: $D_w^Q=MP_{\mathrm{ion}}P_{gr}^Q k'_{R_{50}}k_{\mathrm{ecal}}N_{D,w}^{^{60}\mathrm{Co}}$. The term P_{gr}^Q is not needed with plane-parallel chambers but corrects for gradient effects with cylindrical chambers and is measured in the user's beam. The parameter k_{ecal} is associated with converting the ^{60}Co absorbed-dose calibration factor into one for an electron beam of quality Q_e and contains most of the chamber to chamber variation. Calculated values of k_{ecal} are presented as well as Monte Carlo calculated P_{wall} values for plane-parallel chambers in a water phantom irradiated by a ^{60}Co beam since these are needed to calculate k_{ecal}. The factor $k'_{R_{50}}$ is a function of R_{50} and converts the absorbed-dose calibration factor to that for the electron-beam quality of interest. Two analytical expressions are presented which are close to universal expressions for all cylindrical Farmer-like chambers and for well-guarded plane-parallel chambers respectively. Calculated values are presented graphically for electron beams with energies between 5 and 50 MeV. © *1998 American Association of Physicists in Medicine.* [S0094-2405(97)02212-8]

Dedication: This paper is dedicated to the memory of F. Herb Attix who insisted that there must be an electron-beam equivalent of k_{Q} for photon beams.

I. INTRODUCTION

In external beam dosimetry protocols such as the TG–21 protocol of the AAPM[1] and the TRS-277 Code of Practice of the IAEA,[2] reference dosimetry is a complex process which assigns an absorbed dose to water starting with an air-kerma calibration of an ion chamber. For photon-beam dosimetry, it has been shown that starting from absorbed-dose calibration factors brings many conceptual simplifications.[3–6] It might be expected that starting with absorbed-dose calibration factors would also simplify electron-beam dosimetry, however it is not so straightforward. One significant barrier is that there are no primary standards for electron-beam dosimetry and thus the dosimetry chain must start from an absorbed-dose calibration factor for a photon beam. Another major hurdle concerns the water to air stopping-power ratios which play a central role in the response and hence calibration factors for ion chambers. In photon-beam dosimetry, these stopping-power ratios are almost independent of depth past the depth of dose maximum, d_{max}, whereas in electron beams they are a strong function of depth as well as beam quality. As well as these fundamental issues, recent research has added complexities to the usual procedures. For example, most protocols require the determination of $\overline{E_0}$, the mean electron energy at the phantom surface, but recent research[7] has shown that the best procedures[8] in terms of R_{50} are not very accurate. It has also been shown that stopping-power ratios calculated using incident mono-energetic electron beams are incorrect by between -0.6% and $+1.2\%$ at d_{max} compared to values calculated using incident realistic electron beams.[9] Ding *et al.* presented procedures which gave the necessary corrections to stopping-power ratios for any clinical accelerator, thus getting around these problems.[9] Nonetheless, this makes the procedure even more complex and it still suffers from the two more fundamental problems mentioned above.

Burns *et al.*[10] made the observation that if one defines the reference depth for electron-beam dosimetry as $d_{\mathrm{ref}}=0.6R_{50}-0.1$ (with all quantities in cm) instead of d_{max}, then the water to air stopping-power ratio at d_{ref} is a function of only R_{50}, and this function fully accounts for the realistic nature of the incident electron beam.

The purpose of this paper is to outline a proposal for a new electron-beam dosimetry protocol which has the following features:

- it starts from an absorbed-dose calibration factor for ^{60}Co to make it consistent with the present proposal for the new AAPM photon-beam protocol;[6,11,12]
- it specifies electron-beam quality directly in terms of R_{50}

and uses the reference depth, d_{ref}, recommended by Burns *et al.*;[10]

- it has a formalism which is parallel in many respects to the k_Q formalism for photon-beam dosimetry;
- it fully accounts for the impact on stopping-power ratios of realistic electron beams;
- it allows an easy transition to using primary standards for absorbed-dose to water in electron beams when these are available.

II. A NEW PROPOSAL

The fundamental equations of the k_Q formalism are[3–6]

$$D_w^Q = M P_{\text{ion}} k_Q N_{D,w}^{Q_0} \quad [\text{Gy}], \tag{1}$$

$$N_{D,w}^Q = k_Q N_{D,w}^{Q_0} \quad [\text{Gy/C}], \tag{2}$$

where D_w^Q is the absorbed dose to water (in Gy) at the point of measurement of the ion chamber when it is absent (the center of a cylindrical or spherical chamber and the front of the air cavity in a plane-parallel ion chamber); M is the temperature and pressure corrected electrometer reading in coulombs (C) or meter units (rdg); P_{ion} accounts for ion chamber collection efficiency not being 100%;[1] $N_{D,w}^{Q_0}$ is the absorbed dose to water calibration factor for an ion chamber placed under reference conditions in a beam of quality Q_0; $N_{D,w}^Q$ is the calibration factor in a beam of quality Q; and k_Q accounts for the variation in the calibration factor between beam quality Q and the reference beam quality Q_0. These equations can be applied to electron or photon beams.

Today, in practice, the reference beam quality, Q_0, is ^{60}Co.

The general equation for k_Q is[6]

$$k_Q = \frac{\left[\left(\overline{\frac{L}{\rho}}\right)_{\text{air}}^{w} P_{\text{wall}} P_{fl} P_{gr}^Q P_{\text{cel}}\right]_Q}{\left[\left(\overline{\frac{L}{\rho}}\right)_{\text{air}}^{w} P_{\text{wall}} P_{fl} P_{gr}^Q P_{\text{cel}}\right]_{Q_0}}, \tag{3}$$

where the numerator and denominator are evaluated for the beam quality Q of interest, and the calibration beam quality, Q_0, respectively and the notation for the various quantities follows that of TG-21[1] as extended in Ref. 13 and with the addition of P_{cel}, a correction for the central electrode if it is made of a material different from the chamber walls.[6,14]

By adopting the electron-beam reference depth of Burns *et al.*[10] ($d_{\text{ref}} = 0.6R_{50} - 0.1$ cm), the major terms in Eq. (3), i.e., the stopping-power ratios, become a function of R_{50} only. While as yet unproven, it is reasonable to assume that the other electron-beam quantities (e.g., P_{fl}, P_{cel}) are also well specified by R_{50}. As discussed in Ref. 6, one can calculate most of the quantities in Eq. (3) for k_Q at the reference depth $d_{\text{ref}} = 0.6R_{50} - 0.1$ cm as a function of the parameter R_{50}. These calculations apply for all beams. However, the P_{gr}^Q factor in Eq. (3) depends on the details of the depth-dose curve in the user's beam, and thus must be measured in the user's beam (at least for cylindrical chambers, for plane-parallel chambers it is 1.0). Thus k_Q for electron beams has two components: one, $k_{R_{50}}$, which depends on the chamber but is a function only of the beam quality specifier, R_{50}; and the second, P_{gr}^Q, which extracts the gradient corrections and which, for a cylindrical chamber, depends on the shape of the particular depth-dose curve being measured, i.e.:

$$k_Q = P_{gr}^Q k_{R_{50}}, \tag{4}$$

where

$$k_{R_{50}} = \frac{\left[\left(\overline{\frac{L}{\rho}}\right)_{\text{air}}^{w} P_{\text{wall}} P_{fl} P_{\text{cel}}\right]_{R_{50}}}{\left[\left(\overline{\frac{L}{\rho}}\right)_{\text{air}}^{w} P_{\text{wall}} P_{fl} P_{gr}^Q P_{\text{cel}}\right]_{^{60}\text{Co}}}, \tag{5}$$

and

$$P_{gr}^Q = I(d_{\text{ref}} + 0.5 r_{\text{cav}})/I(d_{\text{ref}}) \quad [\text{for cylindrical chambers}], \tag{6}$$

$$= 1.0 \quad [\text{for plane-parallel chambers}], \tag{7}$$

where $I(d)$ is the ionization reading of a cylindrical chamber placed with the cylindrical axis at depth d and r_{cav} is the radius of the chamber's cavity in cm. Burns *et al.*[10] have shown that the ionization gradient is typically 10%/cm or less at d_{ref}, and hence P_{gr}^Q is within 1.6% of unity for a Farmer-like chamber. This P_{gr}^Q correction is equivalent to using the effective point of measurement for cylindrical chambers recommended in many dosimetry protocols such as the IAEA Code of Practice[2] and the AAPM's TG–25.[8] In the TG–21 protocol this factor is not needed in electron beams since the gradient is taken as zero for measurements at $d_{\max}$. As an aside, in ^{60}Co beams, P_{gr}^Q is conceptually the same as the P_{repl} factor in the TG–21 protocol,[1] but for photon beams, the actual values obtained using the TG–21 approach or the IAEA's effective point of measurement approach are considerably different.[4,13,5]

In the above approach the final dose equation at d_{ref} is:

$$D_w^Q = M P_{\text{ion}} P_{gr}^Q k_{R_{50}} N_{D,w}^{^{60}\text{Co}} \quad [\text{Gy}]. \tag{8}$$

The values of $k_{R_{50}}$ are calculable as a function of R_{50} and only depend on the chamber (see the Appendix). For cylindrical chambers, the user must measure P_{gr}^Q in their own electron beam, but for plane-parallel chambers, $P_{gr}^Q = 1.0$.

A reasonable dosimetry protocol could be designed using this approach, and was essentially proposed by Burns *et al.*[10] (although note that the $k_{R_{50}}$ quantity proposed in Eq. (6) of that paper includes P_{gr}^Q and thus is slightly different from that used here). The only drawbacks are that the values of $k_{R_{50}}$ for different ion chambers vary considerably (see Fig. 1 and Fig. 2) and there is no provision for the day when calibration factors are available for electron beams. Both of these drawbacks can be overcome as follows.

As a first step, consider a system based on $N_{D,w}^{Q_e}$, an absorbed dose to water calibration factor for an electron beam

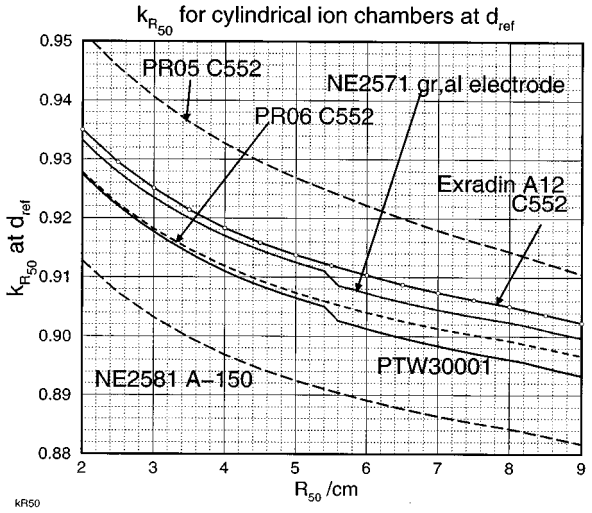

FIG. 1. Calculated values of $k_{R_{50}}$ [Eq. (5)] as a function of R_{50} for several common cylindrical ion chambers. These values can be used with a ^{60}Co absorbed-dose to water calibration factor and Eq. (8) to assign dose to water at the reference depth $d_{\text{ref}}=0.6R_{50}-0.1$ cm.

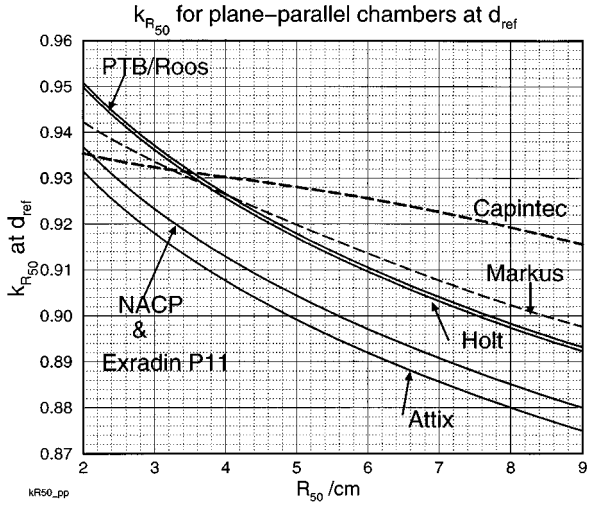

FIG. 2. Calculated values of k_Q ($=k_{R_{50}}$ [Eq. (5)]) as a function of R_{50} for most common plane-parallel chambers. These values are used with a ^{60}Co absorbed-dose to water calibration factor and Eq. (8) and $P_{gr}^{Q}=1.0$ to assign dose to water at the reference depth $d_{\text{ref}}=0.6R_{50}-0.1$ cm.

of arbitrary quality Q_e. In this system the equation for the absorbed dose to water under reference conditions is

$$D_w^Q = MP_{\text{ion}}k'_Q N_{D,w}^{Q_e} \quad [\text{Gy}], \tag{9}$$

where, corresponding to k_Q in Eq. (2), k'_Q is the factor which converts the absorbed-dose calibration factor in an electron beam of quality Q_e to that in a beam of quality Q. From Eq. (3), one can write:

$$k'_Q = \frac{\left[\left(\overline{\frac{L}{\rho}}\right)_{\text{air}}^{w} P_{\text{wall}}P_{fl}P_{gr}^{Q}P_{\text{cel}}\right]_Q}{\left[\left(\overline{\frac{L}{\rho}}\right)_{\text{air}}^{w} P_{\text{wall}}P_{fl}P_{gr}^{Q}P_{\text{cel}}\right]_{Q_e}}. \tag{10}$$

Since both the numerator and denominator refer to electron beams in this case, then for the reference beam quality Q_e, $k'_Q=1.0$ for all chambers, just as $k_Q=1.0$ in a ^{60}Co beam for all chambers.

For the same reasons as given above concerning splitting k_{Q} into 2 components (see Eq. (4)), for k'_Q one writes (from Eq. (10))

$$k'_Q = \frac{P_{gr}^{Q}}{P_{gr}^{Q_e}}k'_{R_{50}} \tag{11}$$

with

$$k'_{R_{50}} = \frac{\left[\left(\overline{\frac{L}{\rho}}\right)_{\text{air}}^{w} P_{\text{wall}}P_{fl}P_{\text{cel}}\right]_Q}{\left[\left(\overline{\frac{L}{\rho}}\right)_{\text{air}}^{w} P_{\text{wall}}P_{fl}P_{\text{cel}}\right]_{Q_e}}. \tag{12}$$

where now two measured gradient corrections are needed because there are gradient corrections in the numerator and denominator of Eq. (10) since there are two electron beams involved. Equation (12) is analogous to Eq. (5) except that now all quantities are evaluated in electron beams.

Using Eq. (2) which defines k_{Q} in terms of the photon-beam absorbed-dose calibration factor, one can write

$$N_{D,w}^{Q_e} = k_{\text{Q}}(Q_e)N_{D,w}^{60_{\text{Co}}} = P_{gr}^{Q_e}k_{\text{ecal}}N_{D,w}^{60_{\text{Co}}}, \tag{13}$$

where the second equality follows from Eq. (4) which separates k_Q for electron beams into its two components, $P_{gr}^{Q_e}$ and k_{ecal}. The quantity k_{ecal} is just $k_{R_{50}}$ evaluated for a beam quality Q_e in Eq. (5), i.e.:

$$k_{\text{ecal}} = k_{R_{50}}(Q_e). \tag{14}$$

Note that Eq. (13) is in terms of the original quantities k_Q and $k_{R_{50}}$ defined earlier.

Starting from Eq. (9) for the dose to water, using Eq. (13) to substitute for $N_{D,w}^{Q_e}$ and Eq. (11) to substitute for k'_Q, one has, after some cancellation,

$$D_w^Q = MP_{\text{ion}}P_{gr}^{Q}k'_{R_{50}}k_{\text{ecal}}N_{D,w}^{60_{\text{Co}}} \quad [\text{Gy}]. \tag{15}$$

Also, from Eq. (13) one has

$$k_{\text{ecal}} = \frac{N_{D,w}^{Q_e}}{P_{gr}^{Q_e}N_{D,w}^{60_{\text{Co}}}}. \tag{16}$$

Thus there are two ways to determine k_{ecal}. The first, based on Eq. (14), is to evaluate Eq. (5) for $k_{R_{50}}$ at beam quality Q_e. Values of k_{ecal} calculated as described in the Appendix, are presented in Tables I and II. This list of cylindrical cham-

TABLE I. Values of k_{ecal} for plane-parallel chambers, calculated as described in the Appendix using Eq. (14) and Eq. (5) or Eq. (A5) with a beam quality Q_e of R_{50}=7.5 cm. For this value of Q_e, Eq. (A5) reduces to $k_{ecal}=0.903/P_{wall}$.

Chamber	k_{ecal}
Attix	0.883
Capintec	0.921
PTB/Roos	0.901
Exradin P11	0.888
Holt	0.900
Markus	0.905
NACP	0.888

bers includes all chamber models (or their equivalents) representing more than 0.3% of ^{60}Co calibrations in the last 2 years at the two largest Accredited Dosimetry Calibration Laboratories at the University of Wisconsin and at K&S Associates. The NE2571, NE2505/3,3A, PTW N30001 (or equivalent N23333) and N31003 (or equivalent N233641), Exradin A12, and Capintec PR06C&G represent more than 83% of all calibrations.

To do these calculations requires knowledge of P_{wall} for plane-parallel chambers irradiated in a water phantom by a ^{60}Co beam and newly calculated values are also presented in the Appendix. For cylindrical chambers, the wall materials and thicknesses are needed to calculate P_{wall} in a water phantom irradiated by a ^{60}Co beam plus the cavity diameter and information about whether the electrode is made of aluminum or the wall material. The second method to determine k_{ecal}, using Eq. (16), requires access to a primary standard for electron beams in order to establish $N_{D,w}^{Q_e}$ and, for cylindrical chambers, also requires knowledge of the gradient correction for the user's chamber in the beam in the primary standards laboratory, i.e., $P_{gr}^{Q_e}$. These factors are not yet available.

One advantage of using Eq. (15) as the basis of a dosimetry protocol, instead of the equivalent Eq. (8), is that the transition to using primary standards for electron beams is made easier. Specifically, once electron-beam absorbed-dose calibration factors are available, one could use the following dose equation:

TABLE II. Values of k_{ecal} for all cylindrical chambers commonly used for reference dosimetry in North America. Values are calculated as described in the Appendix using Eq. (14) and Eq. (5) with an arbitrary beam quality Q_e of R_{50}=7.5 cm. Information about ion chambers required for the calculations is shown, and was obtained directly from manufacturers.

		Wall			
Chamber	k_{ecal}	material	thickness g/cm^2	cavity diameter mm	Al electrode diameter mm
Farmer-like					
Exradin.A12	0.906	C-552	0.088	6.1	
NE2505.3A	0.903	Graphite	0.065	6.3	1.0
NE2505.3B	0.889	Nylon	0.041	6.3	1.0
NE2561	0.904	Graphite	0.090	7.4	1.0
NE2571	0.903	Graphite	0.065	6.3	1.0
NE2577	0.903	Graphite	0.065	6.3	1.0
NE2581	0.885	A-150	0.041	6.3	
PR06C/G	0.900	C-552	0.050	6.4	
PTW23331	0.896	Graphite	0.012	7.9	1.0
		PMMA	0.048		
PTW30001(a)	0.897	Graphite	0.012	6.1	1.0
		PMMA	0.033		
PTW30002	0.900	Graphite	0.079	6.1	
PTW30004	0.905	Graphite	0.079	6.1	1.0
PTW31003(b)	0.898	Graphite	0.012	5.5	1.5(d)
		PMMA	0.066		
Other Cylindrical					
Exradin A1(c)	0.915	C-552	0.176	4.0	
Capintec PR05/5P	0.916	C-552	0.210	4.0	
Wellhofer IC10/IC5	0.912	C-552	0.227	6.0	

[a]PTW30001 has the same values as the PTW23333 it replaced.
[b]PTW31003 has the same values as the PTW233641 it replaced.
[c]There has been a change in designation of Exradin A2/A1 chambers. Model A1 now refers to the Shonka chamber with diameter 4 mm.
[d]Since data only available for 1 mm electrodes, that is what is used in calculations.

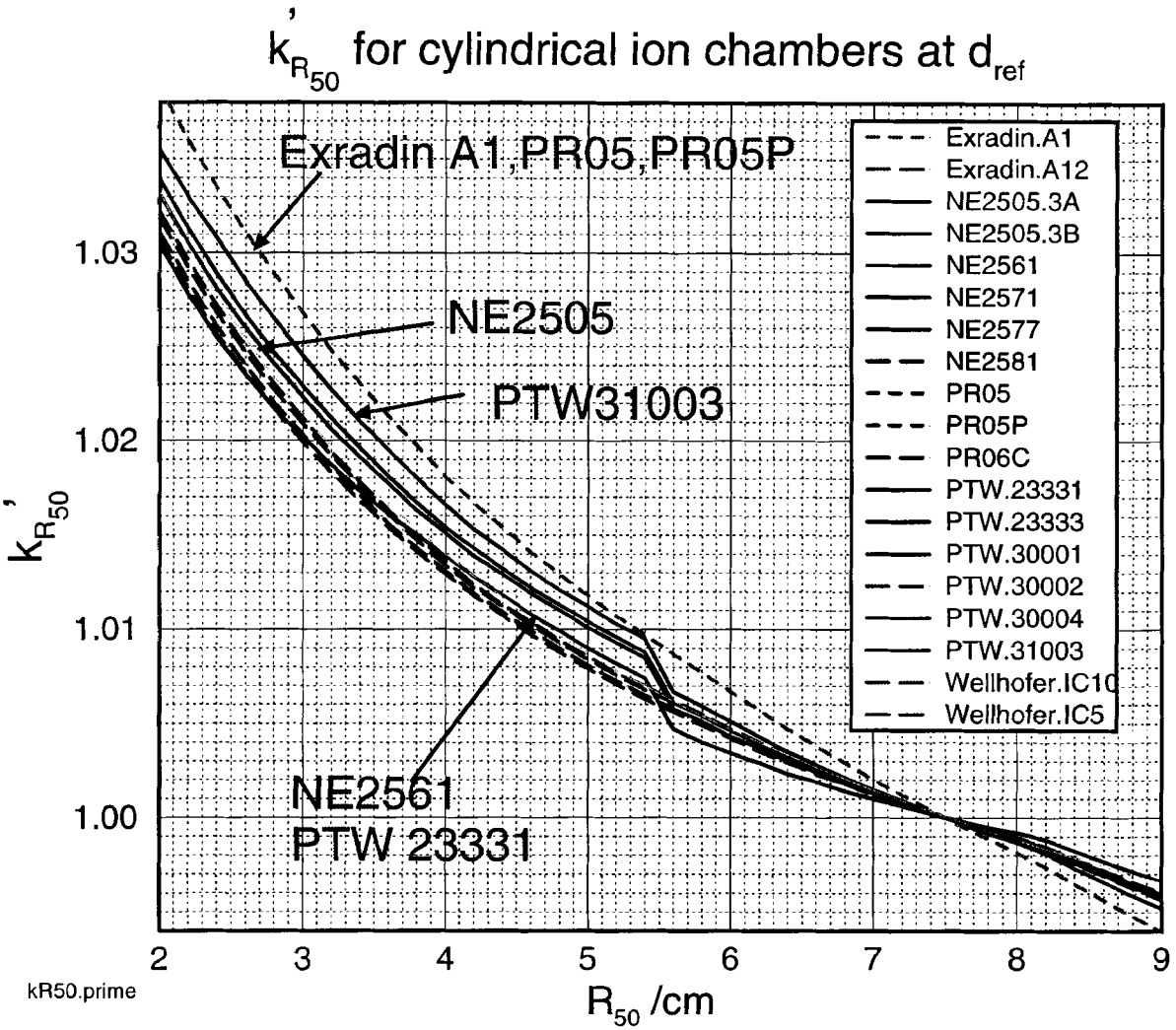

FIG. 3. Calculated values of $k'_{R_{50}}$ [Eq. (12)] as a function of R_{50} for cylindrical ion chambers. These values can be used with Eq. (15) and a measured value of P^Q_{gr} to determine the absorbed dose to water at the reference depth of $d_{\text{ref}}=0.6R_{50}-0.1$ cm. Note that chambers with aluminum electrodes are shown as solid lines. The upper two curves at smaller values or $k'_{R_{50}}$ represent curves which have cavity diameters less than 6 mm (i.e., they are not Farmer-like chambers). Equation (19) reproduces the values for all chambers with diameters greater than 6 mm within 0.2%.

$$D^Q_w = MP_{\text{ion}}\frac{P^Q_{gr}}{P^{Q_e}_{gr}}k'_{R_{50}}N^{Q_e}_{D,w} \quad \text{[cylindrical chambers]} \tag{17}$$

$$= MP_{\text{ion}}k'_{R_{50}}N^{Q_e}_{D,w} \quad \text{[plane parallel chambers]}, \tag{18}$$

where the values of $k'_{R_{50}}$ presented here could be used as long as the calibration factor is for a beam with quality Q_e of $R_{50}=7.5$ cm. This quality is arbitrary but has been selected to be at a high energy since measurements are easier there in general so that primary standards are most likely to be developed there first, and it is attainable at many clinics using electron beams. For cylindrical chambers this would necessitate measurement of $P^{Q_e}_{gr}$ at d_{ref} in the beam at the standards laboratory. Even if one continues to use Eq. (15) based on a ^{60}Co beam calibration factor for electron-beam dosimetry, one could use the electron-beam primary standards and Eq. (16) to measure the values of k_{ecal}.

Another advantage of Eq. (15) is that the values of $k'_{R_{50}}$ show much less chamber to chamber variation than the values of $k_{R_{50}}$. Figure 3 shows calculated $k'_{R_{50}}$ values for cylindrical chambers. Note that all the Farmer-like chambers are virtually identical except for those chambers with aluminum electrodes where a 0.2% effect comes into play below 13 MeV. The PR05, PR05P and Exradin A1 chambers show a slightly different trend because they have a smaller diameter cavity (4 mm) and hence their values of P_{fl} are different. The chambers with aluminum electrodes all show a 0.2% ''jump'' near 13 MeV because the P_{cel} correction has a discontinuity at that point. The following equation reproduces the individual curves within 0.2% for all cylindrical chambers with cavity diameters greater than 6 mm, for 2 cm $<R_{50}<9$ cm:

$$k'_{R_{50}}(cyl)=0.9905+0.071\ \text{e}^{(-R_{50}/3.67)}. \tag{19}$$

Figure 4 shows the calculated values for plane-parallel chambers. Here all the chambers with adequate guard rings have

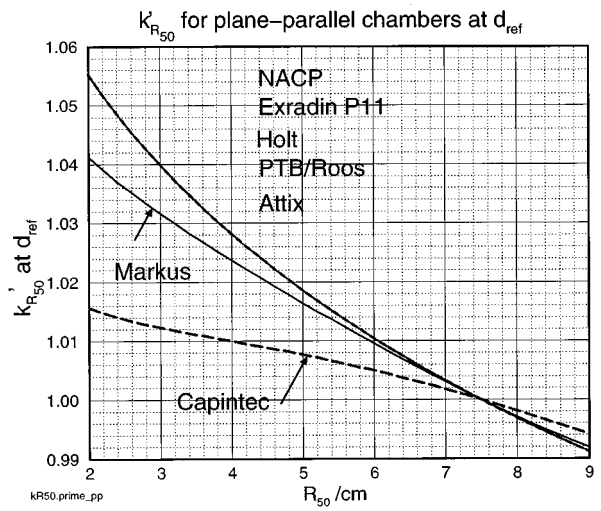

FIG. 4. Calculated values of $k'_{R_{50}}$ [Eq. (12)] as a function of R_{50} for several common plane-parallel chambers. Note that the values for the 5 well-guarded chambers lie on the same line in the figure. These values can be used with Eq. (15) (with $P^Q_{gr} = 1.0$) to determine the absorbed dose to water at the reference depth of $d_{\text{ref}} = 0.6R_{50} - 0.1$ cm.

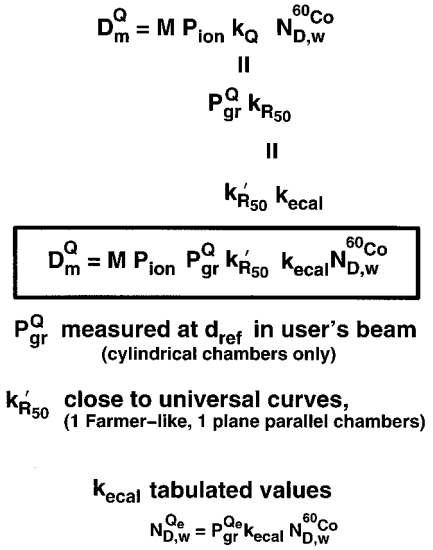

FIG. 5. Summary of the proposal for electron-beam dosimetry. Note that for plane-parallel chambers the factor P^Q_{gr} is unity. Values of $k'_{R_{50}}$ are presented in Figs. 3 and 4 for cylindrical and plane-parallel chambers respectively. Values of k_{ecal} are presented in Tables I and II.

identical values of $k'_{R_{50}}$ while the Markus and Capintec chambers show some deviation because of the electron fluence corrections which become significant at low energies (although this leads to some offset at high energies too since there is still some offset at the reference beam quality with $R_{50} = 7.5$ cm). For the well-guarded plane-parallel chambers, for 2 cm $< R_{50} <$ 20 cm,

$$k'_{R_{50}}(pp) = 1.2239 - 0.145(R_{50})^{0.214}, \tag{20}$$

which is an analytic representation of the curve. Similarly, analytic expressions could be derived for the Markus and Capintec chambers by incorporating the expressions for the P_{fl} (shown in Fig. 8 in the Appendix).

III. DISCUSSION

In summary, by using a reference depth of $d_{\text{ref}} = 0.6R_{50} - 0.1$ cm one can establish a ''k_Q'' protocol for electron-beam dosimetry which has a simple form, and for which most of the chamber to chamber variations can be collected into a single factor, viz., k_{ecal} which must be calculated for the time being using Eq. (5). Calculated values of most commercial ion chambers used for reference dosimetry are given in Tables I and II, based on the calculations described in the Appendix. The advantage of the proposed approach is that once there are primary standards for electron beams, k_{ecal} can be measured based on Eq. (16) as the ratio of absorbed-dose calibration factors in an electron beam and in a ^{60}Co beam. Aside from this k_{ecal} factor, the value of $k'_{R_{50}}$, the remaining chamber dependent factor in the dose equation (Eq. (15)), shows very little chamber to chamber variation as a function of R_{50} for cylindrical or plane-parallel chambers. For Farmer-like chambers or well-guarded plane-parallel chambers, the values of $k'_{R_{50}}$ can be obtained from Eq. (19) or Eq. (20) respectively.

The major complication in this procedure is the need to measure P^Q_{gr} correction factors in the user's beam at d_{ref} if cylindrical chambers are used. It is tempting to define electron-beam absorbed-dose calibration factors in terms of an effective point of measurement, and thus get rid of the need for these P^Q_{gr} correction factors. However, this would require a primary standard to incorporate this chamber dependent feature, and this is undesirable, both because the understanding and the data on this issue are not very good, and because the standards laboratory would become responsible for evaluating a complex factor depending on the design of the user's chamber. A much easier solution is just to use a well-guarded plane-parallel chamber, since these require no gradient correction and furthermore, with the current assumptions, these all have a single ''$k_{R_{50}}$'' curve. Another drawback of using $d_{\text{ref}} = 0.6R_{50} - 0.1$ cm with cylindrical chambers is that there is a significant fluence correction factor, P_{fl}, even for high-energy beams (see Fig. 7 in the Appendix). Once again, this problem can be avoided by the use of plane-parallel chambers.

One aspect of this proposal that needs further investigation is that the fluence correction factor, P_{fl}, is required away from $d_{\max}$, the point at which most previous measurements were done.[15–17] In practice these factors have been parameterized in terms of $\overline{E_z}$, the mean energy at the point of measurement, and in the procedure proposed here, it is assumed that the measured values apply, despite no longer being at $d_{\max}$. The IAEA Code of Practice also makes this assumption when it uses reference depths away from $d_{\max}$.[2] Huq *et al.*[18] have reported recent measurements of P_{fl} at the Burns *et al.* reference depth recommended here. These mea-

surements indicate good agreement with the values of P_{fl} used here for cylindrical chambers in electron beams with initial energies from 5 to 20 MeV.[18]

It must be emphasized that the procedure outlined here is not as complex as the equations might suggest. Figure 5 summarizes the proposal. Starting from $N_{D,w}^{^{60}\mathrm{Co}}$, an absorbed dose to water calibration factor, one needs a single, tabulated chamber dependent factor, k_{ecal}, (Tables I and II), plus a value, $k'_{R_{50}}$ which depends on the beam quality, R_{50}, but which shows very little chamber to chamber variation for either Farmer-like chambers or well guarded plane-parallel chambers (Figs. 3 and 4 and Eq. (19) or Eq. (20)). The final factors which make the equations appear complex are the gradient corrections which are needed for cylindrical chambers only. Although conceptually complex, their values are derived from a simple measurement in the user's beam.

As pointed out by Burns *et al.*,[10] once stopping-power ratios calculated for incident realistic electron beams are used in determining the dose at the reference point, it is essential that these same stopping-power ratios are used when establishing the dose at other depths in phantom. To do this they provided an analytic formula for stopping-power ratios as a function of depth and R_{50} and a fortran routine is available at: http://www.irs.inms.nrc.ca/inms/irs/papers/SPRR50/sprR50.html. Using these stopping-power ratios and the procedures outlined in the AAPM's TG-25 Report[8] for measuring complete depth-dose curves, one is able to accurately and consistently determine the dose at $d_{\max}$, which is where most clinical normalization is done.

The procedure outlined here offers considerable improvement in the accuracy of electron-beam dosimetry compared to the use of TG−21 protocol or the IAEA Code of Practice because it uses improved dosimetric data. For example, in a high-energy electron beam with a 5% bremsstrahlung tail, when using a chamber with an aluminum electrode to assign the dose at $d_{\max}$ using the procedure suggested here, the dose would increase by nearly 2% compared to that assigned by TG-21. In contrast, the dose assigned in a low-energy electron beam would decrease by 0.4% measured with a chamber without an aluminum electrode. Thus the relative dose assigned using TG−21 in these 2 situations would have been wrong by 2.4% compared to the more accurate data used here.

However the approach itself provides little improvement in overall accuracy of electron-beam reference dosimetry compared to the TG-21 formalism, as long as the new physics included here is also included in the TG-21 formalism. The first major issue is the use of stopping-power ratios calculated with incident realistic electron beams. Ding *et al.*[9] have provided data which allows the standard TG-21 stopping-power ratios to be corrected based on the measured value of the bremsstrahlung tail in the user's beam. They showed that this correction varied from −0.6% to 1.2%. The second issue concerns the correction for central electrodes made of aluminum, i.e., P_{cel}. Based on the data of Ma and Nahum,[14] the values of P_{cel} which have been proposed imply up to a 0.7% effect in electron-beam dosimetry.[6] The approach outlined here includes both of these effects with fewer steps, but one cannot say that the formalism has lead to more accuracy in the assigned dose. However, the major uncertainties in electron-beam dosimetry are still in the calculation of the factor k_{ecal} or its equivalent in TG-21 (see Eq. (5) for $R_{50}=Q_e$). The real gain in accuracy in the present approach will be when one can measure k_{ecal} factors using primary standards for absorbed dose in electron beams using Eq. (16).

One drawback of the system proposed is that some plane-parallel chambers appear to have variable dosimetric properties which suggest that ^{60}Co calibrations may not provide accurate indications of behavior in electron beams.[19,20] To the extent that this is the case, this suggests the need for using electron-beam calibration factors which can easily be introduced following the procedure outlined here (Eq. (18)). Alternatively, prior to the availability of these calibration services, one could measure k_{ecal} for each plane-parallel chamber against a cylindrical chamber, much as N_{gas} is determined by measurements in high-energy electron beams for these chambers when following TG-21[1] or TG-39.[17]

One other aspect of this approach is that R_{50} and d_{ref} must be established at the same time as the reference dose measurements are being made to ensure that correct values are used since by moving away from dose maximum one becomes more sensitive to changes in the beam energy. For example, a 3% variation in R_{50} near 6 cm would mean d_{ref} changes by about 1 mm and with a placement uncertainty of say 1 mm this leads to an effective depth uncertainty of 1.4 mm. The uncertainty in the dose at d_{ref} in a worst case situation where there is a 10%/cm gradient[10] is thus 1.4%. Similar concerns apply wherever d_{ref} is selected since the gradient is actually larger near dose maximum for low-energy beams and the placement uncertainty will contribute a similar uncertainty there as at d_{ref}.

IV. CONCLUSIONS

The advantages of this approach are that it starts from a ^{60}Co absorbed-dose calibration factor and allows a formalism which parallels the photon beam case. It also fully accounts for the effects on stopping-power ratios of realistic clinical beams. Finally, the formalism is structured so that once primary standards for electron beams are in place for one beam quality, Q_e, the most complex factor in the procedure, viz., k_{ecal} can be measured. Also, the $k'_{R_{50}}$ factors can be measured as a function of R_{50} if standards are available at the different beam qualities. The use of well-guarded plane-parallel chambers makes the entire procedure much simpler and more robust and is to be encouraged.

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TABLE III. P_{wall} correction factor for plane-parallel chambers in a phantom of the major material of the chamber or water, irradiated by ^{60}Co beams. Uncertainties shown are statistical (68% confidence) and there is an inherent 1% systematic uncertainty. For the in-water case, it is assumed a 1 mm slab of the major material of the chamber is used for waterproofing unless the chamber has its own waterproof front face which is shown in brackets in the last column. Calculations are performed as described in Ref. 22 using a total of 0.5 g/cm^2 extra material unless noted. These results supersede the preliminary results published in Ref. 6. These values are calculated using the electron stopping power data of ICRU Report 37 (Ref. 23). Experimental values for the in-water case are shown in brackets below the corresponding calculated values.

Chamber (major material)	P_{wall} in ^{60}Co beam: in homogeneous phantom previous	in homogeneous phantom present	in water present	Additional material (chamber itself)
Attix (RMISW)	1.015(4)[a]	1.012(3)	1.023(3)	1mm RMISW, 4.0mm H_2O
Capintec PS033 (pst)	0.952(4)[b]	0.948(1)	0.974(3) (0.985[c])	1mm pst, 3.9mm H_2O
Exradin P11 (pst)	1.000(4)[b]	0.994(2)	1.018(1)	3.9 mm H_2O (1mm pst)
Holt (pst)	0.997(4)[b]	0.997(3)	1.004(1)	5mm H_2O (4mm pst)
Markus (PMMA)	1.000(4)[b]	0.992(2)	0.997(2) (1.003[d]) (1.004[c])	1mm PMMA, 3.8 mm H_2O
NACP (graphite)	1.027(3)[b]	1.018(2)	1.018(2) (1.013[d]) (1.026[c])	5mm H_2O (0.1mm mylar, 0.5mm gr)
PTB/Roos (PMMA)		0.995(2)	1.003(2)	6mm H_2O (1mm PMMA)

[a]Attix (Ref. 32) quoting this author's calculations.
[b]Reference 22.
[c]Reference 20.
[d]Reference 33.

work in this area plus Alan Nahum, David Burns, Pedro Andreo and Klaus Hohlfeld for stimulating discussions over the years. Thanks to Carl Ross and the anonymous referee for valuable comments on the manuscript. I also want to thank Andrew Booth for his programming support. Finally, thanks to Larry Dewerd and Tom Slowey for detailed information on which chambers are actually calibrated at their respective ADCLs, and to the ion chamber manufacturer's and their representatives who provided information on their chambers.

APPENDIX: CALCULATION OF k_Q AND $k_{R_{50}}$

Calculation of k_Q for electron beams is considerably more complex than for photon beams since the quantities in the numerator and denominator of Eq. (3) are different, not just the same quantities at different beam qualities as in the photon beam case. As discussed in the text, only $k_{R_{50}}$ (Eq. (5)), or $k'_{R_{50}}$ (Eq. (12)) can be calculated (as opposed to k_Q) since for cylindrical chambers one must measure the gradient correction in the user's electron beam. This Appendix describes the calculation of $k_{R_{50}}$ in detail since once it can be calculated, $k'_{R_{50}}$ and k_{ecal} are straightforward variations. As an aside, although not used here, one can rewrite Eq. (5) for $k_{R_{50}}$ as

$$k_{R_{50}} = \frac{N_{\text{gas}}}{N^{^{60}\text{Co}}_{D,w}} \left[\left(\frac{\bar{L}}{\rho} \right)^{w}_{\text{air}} P_{\text{wall}} P_{fl} P_{\text{cel}} \right]_{R_{50}}, \tag{A1}$$

where the formula for N_{gas} is extended from the TG-21 protocol's equations to include P_{cel}, the correction factor for an aluminum central electrode.

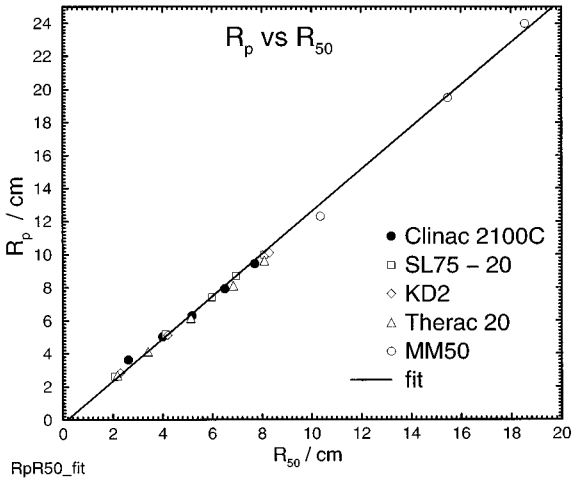

FIG. 6. Values of R_p as a function of R_{50} for a variety of electron-beam depth-dose curves (data taken from Ref. 31). The fitted line is given by Eq. (A4).

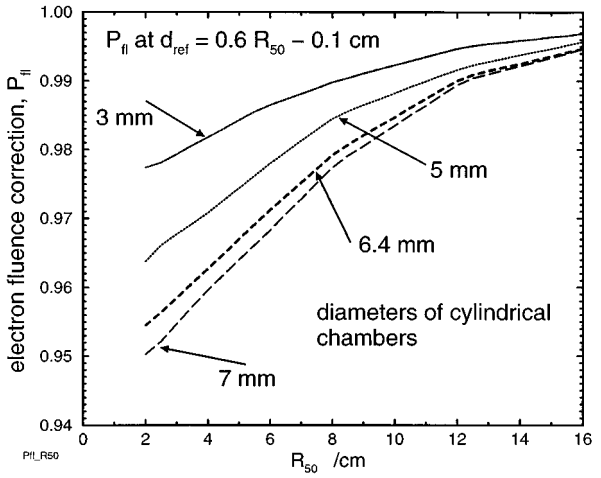

FIG. 7. Values of P_{fl} at a depth of d_{ref} vs R_{50} for cylindrical ion chambers. Based on data in TG–21 from Ref. 15 and using the techniques described in the Appendix to relate the various parameters. The values above $\bar{E}_z = 20$ MeV are obtained by linearly interpolating between the values at 20 MeV and values of 1.0 at 30 MeV for all diameter chambers.

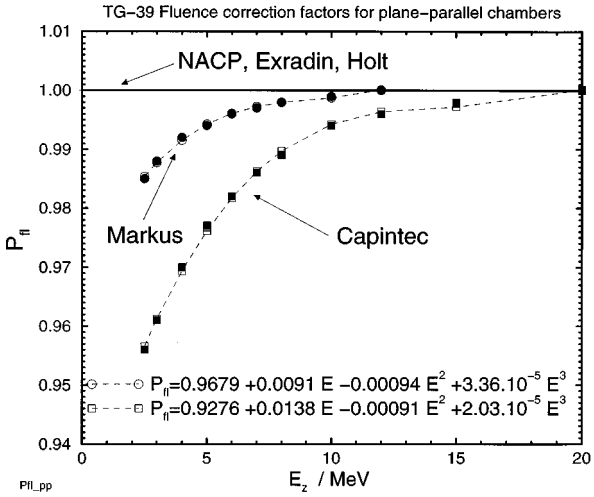

FIG. 8. The P_{fl} factors for plane-parallel chambers recommended by TG–39 (Ref. 17) plus cubic fits to the curves for the Markus and Capintec chambers. The factors are given as a function of $\bar{E}_z$ (E in the figure), the mean energy at the depth of measurement.

For cylindrical chambers, the denominator of Eq. (5), which is for ^{60}Co beams, is calculated as described in Ref. 6. Briefly, the TG-21 formalism is used[1,13,21] to calculate P_{wall} and $P_{gr}^{Q}(=P_{\text{repl}}$ for photon beams); the needed photon-beam data on stopping-power ratios are taken from the IAEA Code of Practice;[2] and a value of $P_{\text{cel}}=0.9926$ is used in a ^{60}Co beam for chambers with a 1 mm aluminum electrode (based on a fit in Ref. 6 to the data in Ma and Nahum[14]).

For plane-parallel chambers the denominator evaluated in ^{60}Co beams requires new considerations. The stopping-power ratio is the same as in the cylindrical chamber case. The P_{repl} factor for plane-parallel chambers is unity. The P_{cel} factor is unity since there are no central electrodes. The P_{wall} factor is not covered by the standard expression for P_{wall}[1,2,13] which only applies to chambers where the wall surrounds the cavity uniformly. For plane-parallel chambers, the front wall is often much thinner than the rest of the chamber and of a different material. Also, any insulator material immediately behind the cavity may have a dramatic effect on the response (up to 5%) and P_{wall} must take this into account.[22,17] In the TG–39 report on electron-beam dosimetry with plane-parallel chambers (which, for consistency with TG–21 did not use the ICRU Report 37 stopping powers[23] being used here), values of P_{wall} in a ^{60}Co beam were provided for the case in which the phantom material matched the major component of the chamber (graphite for an NACP chamber, PMMA for a Markus chamber, etc.). These values were based on Monte Carlo calculations for the chambers free in air with a 0.5 g/cm^2 buildup cap of the same material as the phantom.[22] For the present purposes, the value of P_{wall} in a water phantom is needed, which also implies there may be a waterproofing cap on the plane-parallel chamber. Using the same methods as previously, I have done a further series of Monte Carlo calculations and derived the necessary P_{wall} values for various commercial plane-parallel chambers in a water phantom (see Table III). In this case, if the chamber is not already waterproof, the simulation includes a 1 mm thick slab of material on the front face to make it waterproof. A slab of water is also included in the simulation so that the additional material on the front face totalled 0.5 g/cm^2 in most cases. For comparison, values of P_{wall} are recalculated for the case of the nominally homogeneous phantom using the identical computer code and input data as used previously[22] but for much better statistical precision. The new calculated values are all smaller, on average by 0.5% which is expected to happen about 1 time in 10 on purely statistical grounds. However, recall that there is an inherent 1% systematic uncertainty in these calculations which dominates the overall uncertainty. These new values make the agreement with experiment for non-water phantoms (summarized in Ref. 22) even worse than pointed out elsewhere.[24] Wittkämper *et al.* and Laitano *et al.* have reported measurements of P_{wall} for various chambers in water and these are in reasonable agreement with the calculated values given the respective uncertainties (see Table III).

For calculating P_{wall}, in addition to the values of k_m given previously,[22] values were used of 0.980 and 0.971 for water and RMI solid water, respectively.

With P_{wall} values available, all the factors in the denominator of Eq. (5) are known for plane-parallel chambers. These values of the denominator are calculated and have a relatively large systematic uncertainty. Once it is decided how to waterproof each of these chambers properly, as some of the manufacturers have already done, it would be preferable to have measured values of P_{wall} or perhaps bypass this step entirely and use Eq. (A1) to determine the necessary k_{ecal} values based on measured values of N_{gas}.

For the numerator in Eq. (5) for $k_{R_{50}}$, the stopping-power ratio for electron beams is given by:[10]

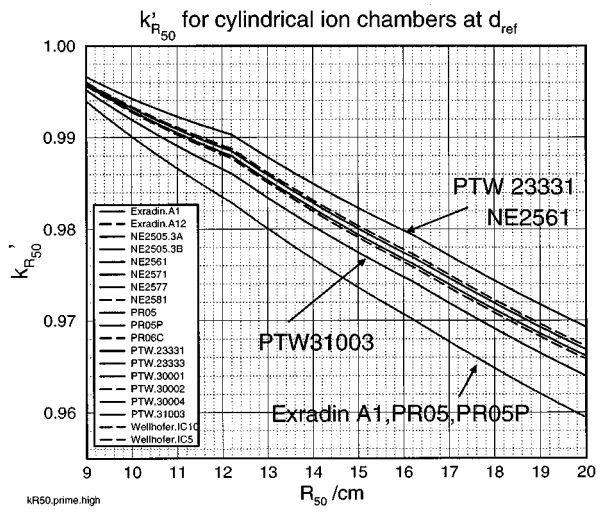

FIG. 9. Calculated values of $k'_{R_{50}}$, Eq. (12), for high-energy electron beams, as a function of R_{50} for cylindrical ion chambers. These values can be used with Eq. (15) and a measured value of P_{gr}^{Q} to determine the absorbed dose to water at the reference depth of $d_{\mathrm{ref}}=0.6R_{50}-0.1$ cm.

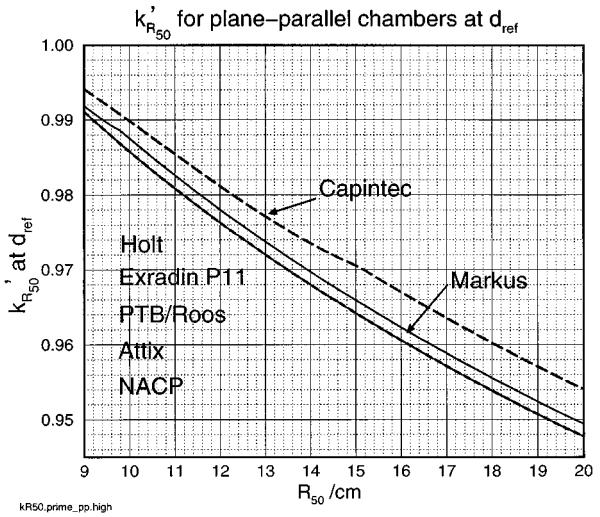

FIG. 10. Calculated values of $k'_{R_{50}}$, Eq. (12), for high-energy electron beams, as a function of R_{50} for plane-parallel chambers. Note that the values for the 5 well-guarded chambers lie on the same line in the figure. These values can be used with Eq. (15) (with $P_{gr}^{Q}=1.0$) to determine the absorbed dose to water at the reference depth of $d_{\mathrm{ref}}=0.6R_{50}-0.1$ cm.

$$\left(\frac{\overline{L}}{\rho}\right)_{\mathrm{air}}^{w}(d_{\mathrm{ref}})=1.2534-0.149(R_{50})^{0.214}. \tag{A2}$$

These values are for the reference depth, $0.6R_{50}-0.1$ cm. Consistent with the conclusions drawn recently by two committees after reviewing the available data,[25,24] the P_{wall} term is taken to be unity, with the caveat that for plane-parallel chambers, there may be a need to include a factor varying between 1.0 and 1.02, depending on the energy and material of the back wall of the chamber.[26–28] For cylindrical chambers, Nahum's theoretical work suggests that if there is any P_{wall} correction, its deviation from unity is less than 1%.[29] The P_{cel} factor for cylindrical chambers with 1 mm aluminum electrodes is 1.0 for $R_{50}\leqslant 5.6$ cm or 0.998 for higher energies as given in Ref. 6 based on the work of Ma and Nahum.[14]

The value of P_{fl} is the remaining unspecified factor in the numerator of Eq. (5) for $k_{R_{50}}$ values. For cylindrical chambers, values of P_{fl} are given in the TG–21 protocol as a function of chamber radius and the mean energy at the point of measurement. One assumes that the values at $d_{\max}$ in TG–21 still apply for d_{ref} away from $d_{\max}$ (further measurements to confirm this, such as those by Huq *et al.*[18] are needed). For low-energy beams the TG–21 values apply because d_{ref} is still at $d_{\max}$. At higher energies, the correction becomes less important and thus the approximation being used is probably acceptable. This same approximation, viz., that values of P_{fl} at a given mean energy measured at $d_{\max}$ hold at other depths, is made for cylindrical chambers in the IAEA Code of Practice[2] which also uses reference depths away from $d_{\max}$. To evaluate P_{fl} requires $\overline{E}_z$, the mean energy at the point of measurement. Traditionally this is given by the Harder relationship:

$$\overline{E}_z=\overline{E}_0(1-z/R_p), \tag{A3}$$

where $\overline{E}_0$ is the mean energy at the surface and R_p is the practical range.[30,1] This parameterization breaks with the proposed beam quality specification in terms of R_{50}. However, it is possible to recast the data on P_{fl} so that the value of P_{fl} at d_{ref} is given as a function of R_{50} and the cavity radius. An approximate value of $\overline{E}_0$ is given by $2.33R_{50}$ and fitting data for R_p and R_{50} from many (21) realistic electron depth-dose curves[31] (see Fig. 6), one can write:

$$R_p=1.271R_{50}-0.23 \quad [\mathrm{cm}]. \tag{A4}$$

While this is a rather crude approximation, the maximum error in the estimate of P_{fl} for a plane-parallel chamber would occur for the Capintec chamber at d_{ref} in the low-energy Clinac beam in Fig. 6 and in this case the incorrect value of $\overline{E}_z$ based on using Eq. (A4) rather than the actual value of R_p would lead to a 0.3% error in P_{fl}. Using Eq. (A4) would lead to a maximum error of 0.14% in P_{fl} for Farmer-like cylindrical chambers in the same beam at d_{ref}.

Putting these relationships together leads to the fluence correction data for cylindrical chambers in Fig. 7. Note that because the reference depth, d_{ref}, is deeper than $d_{\max}$ for high energies, the P_{fl} correction is significant, even at high energies (it is about 0.98 for a Farmer-like chamber at d_{ref} in a 20 MeV beam).

For well-guarded plane-parallel chambers, P_{fl} is taken as unity, but this is not the case for the Markus and Capintec chambers. For these chambers, TG-39 has recommended values for P_{fl} as a function of $\overline{E}_z$, the mean energy at the depth of measurement, and TG-39's tabulated P_{fl} values are given here by the expressions in Fig. 8. The techniques described above for estimating $\overline{E}_z$, the mean energy at d_{ref}, are used to establish P_{fl} at d_{ref}. As with the cylindrical chambers, most data for these chambers have been measured at $d_{\max}$ and possibly do not apply at other depths, but it is assumed here

that they do. For well-guarded plane-parallel chambers, since $P_{fl} = 1.0$, most other factors are common and one can write:

$$k_Q = k_{R_{50}} = \frac{1.2534 - 0.149(R_{50})^{0.214}}{1.134 P_{\text{wall}}}, \quad \text{(A5)}$$

where 1.134 is the Spencer–Attix water to air stopping-power ratio in a ^{60}Co beam.

At this point, all the information needed to calculate $k_{R_{50}}$ for cylindrical or plane-parallel chambers has been presented. Using this same information one can calculate the quantities $k'_{R_{50}}$ (Eq. (12)) and k_{ecal} (which is just a specific value of $k_{R_{50}}$ (Eq. (5) or Eq. (A5)) for the beam quality Q_e.

The calculations reported here can be done using a program called PROT[21] which will be made available on the WWW at http://www.irs.inms.nrc.ca/inms/irs/PROT/PROT_homepage/prothome.html

In the text of the paper the range of values shown for various parameters is for R_{50} between 2 cm (about 5 MeV) and 9 cm (over 20 MeV). However, the calculations have been done for beams up to 50 MeV to cover the use of the MM50 accelerator. The data for these high energy machines are shown in Figs. 9 and 10.

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