Invited Paper

RADIATION DOSIMETRY WITH PLANE-PARALLEL IONIZATION CHAMBERS: AN INTERNATIONAL (IAEA) CODE OF PRACTICE

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Abstract

Research on plane-parallel ionization chambers since the IAEA Code of Practice (TRS-277) was published in 1987 has expanded our knowledge on perturbation and other correction factors in ionization chamber dosimetry, and also constructional details of these chambers have been shown to be important. Different national organizations have published, or are in the process of publishing, recommendations on detailed procedures for the calibration and use of plane-parallel ionization chambers. An international working group was formed under the auspices of the IAEA, first to assess the status and validity of IAEA TRS-277, and second to develop an international Code of Practice for the calibration and use of plane-parallel ionization chambers in high-energy electron and photon beams. The purpose of this work is to describe the forthcoming Code of Practice.

1. INTRODUCTION.

The advantages of using plane-parallel ionization chambers in the dosimetry of therapeutic electron beams have been recognised in all dosimetry protocols. The design characteristics, mainly regarding the shape and size of the collecting volume, make this instrument theoretically ideal for measurements in regions with large dose gradients in the beam direction.

A number of chambers are available today, a few of them having completely new designs, with practically negligible perturbation effects in electron beams. Large correction factors have been found, however, for other chambers, mainly at low electron energies. There is still controversy on the use of plane-parallel chambers for photon beam dosimetry. Most chambers are far from homogeneous in their construction as, in general, materials with different scattering and absorption properties are used in the various walls. It is likely that these effects approximately balance other effects in electron beams, but measurements and calculations in photon beams have shown the need for correction factors to account for the different materials in the chamber. This suggests that plane-parallel chambers should mainly be used for absorbed dose determinations in electron beams but only for relative measurements in photons. The remaining problem is the calibration of the chamber.

The lack of details on dosimetry procedures using plane-parallel chambers, particularly regarding their calibration or a practical determination of the N_D (N_{gas}) chamber factor, has been one of the major criticisms made of the IAEA Code of Practice, TRS-277 [1] where only a reference to the procedures described by NACP [2] was made. It was considered that these procedures were well established and therefore still to be recommended. The influence of the central electrode correction for cylindrical chambers in TRS-277, however, added an unexpected complication to experimental determinations of N_D based on a comparison in electron beams [3].

Research in the field since IAEA TRS-277 was published has expanded our knowledge on perturbation and other correction factors in ion-chamber dosimetry, and also constructional details of the chambers have been shown to be important. Different national organisations have published [4, 5] or are in the process of publishing [6, 7] recommendations including detailed procedures for the use of plane-parallel chambers. An international working group was formed under the auspices of IAEA, first to assess the status and actual validity of IAEA TRS-277 [1] and second to develop an international Code of Practice for the use of plane-parallel ionization chambers in high-energy electron and photon beams. The purpose of this work is to describe the new Code of Practice. Further details on the present situation regarding correction factors and quantities briefly discussed here can be found in [3].

2. AN OVERVIEW OF THE NEW CODE OF PRACTICE.

The contents of the Code of Practice is shown in Table I. It can be observed that together with a rather conventional distribution of the different sections 1-9, Section 10 contains a summary

TABLE I. CONTENTS OF THE *IAEA CODE OF PRACTICE* FOR PLANE-PARALLEL IONIZATION CHAMBERS

1. Introduction
2. Update of the information in TRS-277
3. Equipment
4. Beam quality specification
5. N_K-based formalism and determination of $N_{D,air}$ for plane-parallel ionization chambers
6. N_{D,w,Q_o}-based formalism and determination of N_{D,w,Q_o} factors for plane-parallel ionization chambers
7. Use of plane-parallel chambers in electron beams
8. Use of plane-parallel chambers in photon beams
9. The uncertainty in absorbed dose determination at the reference depth using plane-parallel chambers in electron beams
10. A **Code of Practice** for the calibration and use of plane-parallel ionization chambers

Appendix A. Worksheets

Appendix B. Stopping-power ratios in clinical electron beams.

Appendix C. Chamber perturbation factors in electron and photon beams of all the procedures and data required; this Section is effectively the Code of Practice. The report also contains Appendices where different topics are covered in detail; they also include Worksheets.

The new Code updates information in IAEA TRS-277 regarding recent developments in radiotherapy dosimetry. In most cases differences from existing values or the magnitude of new corrections, are within half a percent but developments (and clarifications) in the field are taken into account. Of special interest for the calibration and use of plane-parallel ionization chambers are

- the effect of metallic central electrodes in cylindrical ionization chambers (included in TRS-277 as a global factor) has been separated into two components, one at the Co-60 calibration (k_{cel}=1.006 for a Farmer-type chamber) and therefore entering into $N_{D,air}$ [1], and another at reference measurements in a phantom (for a Farmer-type chamber p_{cel}=0.994 in Co-60; p_{cel}=0.998 in electron beams). This yields a global correction equal to 1.004 in electrons. It should be noted that cylindrical ionization chambers are used as reference instruments for the calibration of plane-parallel ionization chambers in most calibration alternatives. New values for these corrections, based on Monte Carlo calculations, are adopted [8]. The new expression for $N_{D,air}$ for cylindrical ionization chambers becomes

$$N_{D,air} = N_K(1-g)\,k_{att}k_mk_{cel} \qquad (1)$$

- a procedure based on an absorbed-dose-to-water calibration factor, $N_{D,w}$, is also introduced. This symbol was given in TRS-277 but in practice its use was restricted to low-energy X-rays. It is now becoming available for high-energy photons. At present the most common approach is to provide users with $N_{D,w}$ at a reference quality Q_o, usually ^{60}Co, and apply *beam quality* correction factors for other beam qualities. Users should be warned of the possibility of confusion arising from the notation N_D used by AAPM TG-21 [9] for the $N_{D,w}$ factor.

- a new scaling procedure for conversion of depths and ranges measured in plastic to equivalent quantities in water is given; this is based on the concept of *detour factors* as an alternative to ratios of csda ranges [10].

- a correction for the non-medium equivalence of the chamber wall material, p_{wall}. This factor has implicitly been assumed to be unity in electron dosimetry protocols to date. There is however considerable experimental evidence that this factor may not be unity for certain plane-parallel chamber designs; the probable mechanism here is backscattering differences between the material behind the cavity and that of the wall material. However only values for an *overall* perturbation factor p_Q=p_{cav} p_{wall} are given; p_{cav} replaces p_u as the correction for the in-scattering effect in gas cavities.

- new calculations of stopping-power ratios water/air, $s_{w,air}$, using several independent Monte Carlo codes where different density effect corrections were taken into account. Compared with the stopping-power ratios in TRS-277, differences are small for the electron energies most commonly used in radiotherapy, being close to 0.5% at most depths. The recommendation for the small change is justified in terms of the lack of ambiguity in the corrections used and the higher accuracy of the present set of data.

- the determination of the recombination correction factor for plane-parallel ionization chambers using the "two-voltage" method has been shown to have limitations for most chambers due to the lack of linearity of saturation curves in the region of interest. In order to decrease the influence in the dosimetry procedure it is recommended to use the same voltage ratio for the determination of $N_{D,air}$ and for the absolute dose determination.

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[1] Note that the factor N_D in TRS-277 is now denoted by $N_{D,air}$ in order to distinguish it from $N_{D,w}$, the factor in terms of absorbed dose to water.

Section 3 provides detailed description on phantoms and equipment available, with emphasis on the properties of plane-parallel ionization chambers both for electron and photon radiation. Chambers of new design (Attix, Roos, etc) are included in the compilation. As in TRS-277, water is the recommended reference medium although plastics may be used for measurements at low electron energies. Emphasis is given, however, to the high accuracy achievable today with modern equipment in positioning ionization chambers in water phantoms which thus minimizes the need to use plastic phantoms.

The uncertainty in absorbed dose determination at the reference point using the recommended procedure for determining $N_{D,air}$ is treated in detail, separating the different steps of the dosimetric procedure in a similar way to TRS-277 but incorporating an updated evaluation of uncertainties in the different steps. Uncertainties are also evaluated for the alternative calibration methods based on measurements in photon beams.

Further details on certain sections follow.

2.1. Beam quality specification

The specification of the quality of the beams used for the calibration of plane-parallel ionization chambers follows the recommendations given in TRS-277. As mentioned in the introduction, absolute dosimetry is to be performed in electron beams only, as is the recommended calibration procedure (see below).

For dosimetry purposes it has become customary to specify the quality of electron beams in terms of the mean energy at the surface of the phantom, $\bar{E}_o$, determined from empirical relationships between electron energy and the 50% range in water, R_{50}. $\bar{E}_o$ is needed for the selection of different quantities and parameters in the formalism, and mainly affects the choice of stopping-power ratios water to air, $s_{w,air}$, at the reference depth, namely $s_{w,air}(\bar{E}_o, z_{ref})$. As in IAEA TRS-277 [1] and most dosimetry protocols, the recommendation is to determine $\bar{E}_o$ using the energy-range relationship

$$\bar{E}_o = C\, R_{50}\, MeV \tag{2}$$

where C=2.33 MeV cm^{-1} and R_{50} is obtained from a depth-dose distribution measured with constant source-chamber distance. As is well known, when the dose distribution has been obtained with a constant source-surface distance (SSD=100 cm) Eq. (2) is not strictly valid. As an alternative IAEA TRS-277 has provided tabulated data for determining $\bar{E}_o$ either from ionization curves measured at SSD=100 cm with an ionization chamber or from depth-dose distributions at SSD=100 cm, measured for instance with solid state detectors. These data can be fitted with the following second order polynomial:

$$\bar{E}_o = 0.818 + 1.935\, R_{50}^J + 0.040\, (R_{50}^J)^2 \tag{3}$$

for R_{50}^J determined from a depth-ionization curve and

$$\bar{E}_o = 0.656 + 2.059\, R_{50}^D + 0.022\, (R_{50}^D)^2 \tag{4}$$

for the case of a depth-dose curve, R_{50}^D. For energies above 3 MeV, Eqs. (3) and (4) yield stopping-power ratios, water-to-air, that on the average agree within 0.2% up to depths equal to 0.80 R_p with $s_{w,air}$ values obtained with $\bar{E}_o$ derived from TRS-277 Table IV, with a maximum deviation of 0.4% close to 12 MeV.

Improved energy-range relationships between $\bar{E}_o$ and R_{50}, based on Monte-Carlo calculations for mono-energetic electron beams, have been developed[3, 11] but all yield $\bar{E}_o$ values higher than the above expression. This would result in lower stopping-power ratios at the reference depth compared to those obtained with $s_{w,air}(\bar{E}_o, z_{ref})$ and $\bar{E}_o$ from Eq. (2).

2.2. Determination of $N_{D,air}$ for plane-parallel chambers

Several different methods have been proposed by Mattsson *et al* [12] for obtaining the absorbed-dose-to-air chamber factor $N_{D,air}$ for a plane-parallel chamber. These methods fall into two broad categories. In the first one, a Standards Laboratory calibrates the chamber in terms of N_K and then $N_{D,air}$ is obtained theoretically.

In the second one, the user determines $N_{D,air}$ directly by experimental intercomparison with a reference ion-chamber having a known $N_{D,air}$ factor. Both chambers are alternatively positioned at a reference depth in a phantom and the unknown $N_{D,air}$ is obtained from equating the absorbed doses with the two chambers. These procedures have been extensively discussed in Ref. [13] and in the recent TG-39 protocol of the AAPM [14]. Methods in the second category are generally performed in the user's beam, either ^{60}Co or high-energy electrons [12]. It can be noted that this method can in principle be applied to determining $N_{D,air}$ for any chamber that is to be used in electron or photon beams e.g. a second cylindrical chamber provided that $N_{D,air}$ is already known for a reference chamber [4, 15]. Consequently the chamber to be calibrated (not necessarily plane-parallel) and the reference chamber will be denoted by x and ref respectively.

The primary recommendation is the use of a high-energy electron beam. Following the formalism in TRS-277, and equating the absorbed dose at the reference depth with the two chambers, the expression for $N_{D,air}$ for the chamber x to be calibrated, becomes

$$N_{D,air}^{x} = N_{D,air}^{ref} \frac{M^{ref}}{M^{x}} \frac{p_{wall}^{ref} p_{cav}^{ref} p_{cel}^{ref}}{p_{wall}^{x} p_{cav}^{x} p_{cel}^{x}} \qquad (5)$$

where the numerator and denominator correspond to the D_w determination using the reference chamber (usually cylindrical) and chamber x respectively, and the stopping-power ratios cancel out. M^{ref} and M^{x} are ratios of the readings of the two chambers to those of an external monitor to take into account possible accelerator output fluctuations. They must be corrected for the polarity effect, for recombination, and for temperature and pressure. Note that p_{wall}^{ref} for the reference chamber is unity as recommended reference cylindrical chambers are assumed to have negligible wall effects in electron beams [16, 17]. For most plane-parallel ionization chambers and at the energies recommended for the calibration, the factors p_{cav}^{x} and p_{wall}^{x} are practically unity. The factor p_{cel}^{x} is not relevant for plane-parallel ionization chambers but as the procedure can also be extended to cylindrical ion chambers it has been retained in this Eq. For the case of x being a cylindrical chamber the value of p_{cav}^{x} should be interpolated from the data from Johansson *et al* [16] given in TRS-277 Table XI..

The phantom material should preferably be the same as that used for the absolute dose determination. This automatically ensures that the overall effects of any perturbation due to differences in backscattering between the material behind the cavity and that of the phantom (i.e. the component of p_Q due to p_{wall}) will be minimized. Water is the preferred material. The energy of the electron beam should be as high as possible in order to minimise the perturbation due to the air cavity of the reference chamber. As a guide p_{cav}^{ref} should be within 2% of unity. For a cylindrical reference chamber with an internal radius of 3 mm (approximately Farmer type) this means that $\bar{E}_o$ should be no lower than 15 MeV but should preferably be as high as possible; the lower limit on $\bar{E}_o$ may be lowered if the chamber radius is smaller. The depth should be the same as the reference depth z_{ref} used for absorbed dose determination in the chosen high-energy beam. The SSD should be 100 cm and the field size should be approximately 12 cm x 12 cm or larger - this is not critical. The chambers are to be placed with their respective effective points of measurement, P_{eff}, at the same depth. A Farmer-type chamber, i.e. approximately 6 mm internal diameter and 1 mm electrode diameter, for the reference cylindrical chamber is recommended here as a great deal of experience has been gained with such chambers and the correction factors can be said to be well known [18, 19]. The choice of a chamber with a radically different geometry, e.g. a very thick central electrode, can lead to larger uncertainties.

Alternative methods for obtaining the absorbed-dose-to-air chamber factor $N_{D,air}$ for a plane-parallel chamber based on measurements made in a ^{60}Co beam have been introduced. They are classified into two categories generally depending on the institution where the calibration is performed. The *in-phantom* method is generally performed in the user's beam at the Hospital, although it can also be performed at the Standards Laboratory. Measurements free in air are usually performed in a ^{60}Co beam at the Standards Laboratory.

The calibration in a ^{60}Co beam at depth in a phantom has been described by several authors. First by Mattsson *et al* [12] and then in more detail by Attix [20]. The approach is based upon the determination of $N_{D,air}$ from the knowledge of the absorbed dose in the phantom determined with a calibrated reference chamber, like that recommended in the electron-beam method, but in this case irradiated with a ^{60}Co beam. The formalism yields:

$$N^{pp}_{D,air} = N^{ref}_{D,air} \frac{M^{ref}}{M^{pp}} \frac{p^{ref}_{wall}\, p^{ref}_{cel}}{p^{pp}_{wall}} \qquad (6)$$

where p^{ref}_{wall} and p^{ref}_{cel} are perturbation factors of the reference chamber at ^{60}Co; p^{ref}_{cel} is unity for a graphite electrode and 0.994 for a Farmer-type chamber. The standard SSD for a ^{60}Co unit and a field size of 10 cm x 10 cm at the surface should be used. In this method the effective point of measurement for both chambers should be placed at a reference depth of 5 g cm^{-2} in a phantom that matches the plane-parallel chamber material (to minimise p^{pp}_{wall}) or in water if the p^{pp}_{wall} factor is known. For cylindrical chambers in ^{60}Co beams P_{eff} is positioned at a distance equal to 0.6 r from the centre of the chamber.

It is important to note that when a non-water phantom is used, TRS-277 does not provide a direct determination of the perturbation p_{wall} at ^{60}Co as absorbed dose should only be determined in a water phantom. The perturbation factor of the reference chamber is determined according to the general equation that takes into account the thin waterproofing plastic or rubber sleeve normally used to protect the chamber in a water phantom (see also Refs. [21, 22]):

$$p^{ref}_{wall} = \frac{\alpha\, s_{wall,air}\, (\mu_{en}/\rho)_{med,wall} + \tau\, s_{sleeve,air}\, (\mu_{en}/\rho)_{med,sleeve} + (1-\alpha-\tau)\, s_{med,air}}{s_{med,air}} \qquad (7)$$

where *med* is the phantom material and α and τ the fractions of ionization due to electrons arising from the wall and waterproofing sleeve respectively. A fit to the available data for α [23] is given. By applying this fit to the combined thickness of the wall and the sleeve, and substracting α from this, an expression for τ is obtained. This insures that $\alpha+\tau \leq 1$.

The perturbation factor p^{pp}_{wall} in ^{60}Co beams is the major source of uncertainty in this procedure and the reason why the electron-beam method for the calibration of plane-parallel ionization chambers is the preferred option in the new Code of Practice. Differences in p^{pp}_{wall} close to 2% have been reported, either between Monte-Carlo calculations and experimental data [24], or due to chamber-to-chamber variations for chambers of the same type (from the same or from different manufacturers) [25]. It has to be emphasised that p^{pp}_{wall} depends on the phantom material used for the calibration.

The calibration-in-air method is similar to the free in air approach used with cylindrical chambers in Standard Laboratories. The air-kerma rate, free in air, must be known at the position of the cavity centre and N_K of the plane-parallel ionization chamber is then determined. The plane-parallel ionization chamber with appropriate build-up material is placed free in air in a ^{60}Co beam, its center positioned at the point where K_{air} is known. The build-up material should have the same outer dimensions as the chamber and preferably be of the same material as the predominant material of which the chamber is constructed. The procedure yields the N_K calibration factor of the plane-parallel chamber

$$N_K^{pp} = \frac{K_{air}}{M^{pp}} \tag{8}$$

and if the product $k_{att}\,k_m$ is known $N_{D,air}$ is determined according to the well-known expression

$$N_{D,air}^{pp} = N_K(1-g)\,k_{att}\,k_m \tag{9}$$

where for plane-parallel ionization chambers k_{cel} is not involved. In principle this procedure is used together with a *universal* value of $k_{att}\,k_m$ for a given type of plane-parallel ionization chamber. The limitations of this approach increase considerably the estimated uncertainty.

2.3. Determination of N$_{\mathbf{D,w}}$ for plane-parallel chambers

The formalism for the determination of absorbed dose to water in photon and electron beams using a $N_{D,w}$-based calibration factor has been given in detail by Hohlfeld [26]. The absorbed dose to water at the reference point of the chamber (where the calibration factor applies) in a phantom irradiated by a beam of reference quality Q_o is given by the simple relationship

$$D_{w,Q_o} = M_{Q_o}\,N_{D,w,Q_o} \tag{10}$$

where $N_{D,w,Qo}$ is obtained at the Standard Laboratory from the knowledge of the standard quantity absorbed dose to water at the point of measurement in water for the calibration quality Q_o.

Efforts are at present being addressed to providing $N_{D,w,Q}$ calibrations for photon beams, mainly ^{60}Co gamma-rays and to a lesser extent high-energy photon and electron beams [27-31]. A practical approach in common use is to provide users with $N_{D,w,Co}$, i. e. calibration at the reference quality ^{60}Co, and apply *beam quality* correction factors k_Q for other beam qualities [26, 32]. For beams other than the reference quality the absorbed dose to water is then given by

$$D_{w,Q} = M_Q\,N_{D,w,Q_o}\,k_Q \tag{11}$$

where the factor k_Q corrects for the difference between the reference beam quality Q_o and the actual quality being used, Q. k_Q should ideally be determined experimentally at the same quality as the user's beam, although this is seldom achievable. When no experimental data are available an expression for k_Q can be derived comparing Eq. (11) with the formalism in TRS-277; this ensures consistency with the $N_{D,air}$ procedure when k_Q is calculated with the data in TRS-277 [26, 33, 34]. In therapeutic electron and photon beams the general assumption of $(W_{air})_Q=(W_{air})_{Qo}$ yields the equation for k_Q

$$k_Q = \frac{\left(s_{w,air}\right)_Q}{\left(s_{w,air}\right)_{Q_o}}\,\frac{p_Q}{p_{Q_o}} \tag{12}$$

which depends only on ratios of stopping-power ratios and perturbation factors. It should be noted that the chamber-dependent correction factors k_{att}, k_m and k_{cel} are not involved in the definition of k_Q. The only chamber specific factors involved are the perturbation correction factors p_Q and p_{Q_o}.

The connection between the $N_{D,air}$ and the $N_{D,w}$ based formalisms is established by the relationship,

$$N_{D,w,Q} = N_{D,air}(s_{w,air})_Q \, p_Q \tag{13}$$

In principle Eq. (13) could be used to determine $N_{D,air}$ independent of the factors k_{att}, k_m and k_{cel}.

The use of ^{60}Co as reference quality for determining N_{D,w,Q_o} for plane-parallel ionization chambers is an attractive possibility, especially for most SSDLs. Using the formalism at other qualities (both high-energy electron and photon beams) requires, however, the knowledge of p_{Q_o} at ^{60}Co in Eq. (12) which enters in k_Q; this is the main drawback of this procedure. This is also the case for the alternative option which enables users to determine N_{D,w,Q_o}^{pp} directly by experimental intercomparison in a ^{60}Co beam with a reference ion-chamber (cylindrical in this case, where p_Q is more precisely known) having a known N_{D,w,Q_o}^{ref} factor.

It is assumed that the water absorbed dose rate is known at 5 cm depth in a water phantom for ^{60}Co gamma rays. The plane-parallel chamber is placed with its reference point at a depth of 5 cm in a water tank where the absorbed dose to water D_w is known and $N_{D,w,Co}^{pp}$ obtained from

$$N_{D,w,Co}^{pp} = \frac{D_w}{M^{pp}} \tag{14}$$

D_w is obtained using a reference chamber having a calibration factor $N_{D,w,Co}^{ref}$. The calibration factor for the plane-parallel chamber becomes

$$N_{D,w,Co}^{pp} = N_{D,w,Co}^{ref} \frac{M^{ref}}{M^{pp}} \tag{15}$$

where it is assumed that the centre of the reference chamber is positioned at the depth of measurement. The alternative use of P_{eff} is also a valid option. All experimental conditions are identical to those for the determination of $N_{D,air}$ in ^{60}Co using in-phantom measurements.

2.4. Use of plane-parallel chambers

The use of plane-parallel ionization chambers both in electron and in photon beams is considered in line with the introduction above.

2.4.1. Reference conditions

In electron beams, reference conditions consider a reference depth z_{ref} (as in TRS-277) instead of the depth of maximum absorbed dose used in other dosimetry protocols. The absorbed dose to water is determined according to

$$D_w(z_{ref}) = M_u \, N_D \, s_{w,air} \, p_Q \tag{16}$$

where

$$p_Q = p_{cav} \, p_{wall} \tag{17}$$

Note that the perturbation factor p_u in TRS-277 is replaced here by p_Q which is the product of two factors (Eq. (17)). The first, p_{cav}, is the electron fluence perturbation factor, identical to the p_u factor in TRS-277 Table XI. The change in symbol attempts to emphasise that it is exclusively concerned with effects due to the air cavity, rather than the wall material, that is, a correction for the effect known as *in-scattering* where electron tracks are scattered by the medium towards the air cavity. It is stressed that p_{cav} is strictly known at the reference depth only. The second factor p_{wall} takes into account the lack of backscatter of the back wall material compared to water, and has implicitly been assumed to be unity in electron dosimetry protocols to date. This factor is discussed in detail in Appendix C. It was not possible to make definitive recommendations regarding p_{wall} due to the present lack of consensus in the literature [35, 36]. However, all experimental determinations of perturbation in plane-parallel ionization chambers have effectively been of the overall factor p_Q. Figure 1 shows the values recommended for various plane-parallel chambers in the new Code of Practice.

Regarding water/air stopping-power ratios, new calculations have been performed [39] including the two sets of density-effect in water given in the ICRU-37 electron stopping power tables. They are density-effect corrections according to the Sternheimer's model and the more accurate calculations of Ashley based on semi-empirical dielectric-response functions (DRF). It was argued [39] that for electron energies used in radiotherapy, where the density effect in air is negligible, δ_{DRF}-based water/air stopping-power ratios provide a more accurate set of data. Differences in stopping-power ratios due to the different evaluations of the density effect correction are within 1%. The information on the density-effect correction in the set of values actually in use in TRS-277 and in other dosimetry protocols is, however, ambiguous. A new set of data is provided here based on Ashley density-effect corrections for water, Table II. Compared with the stopping-power ratios in TRS-277 differences are negligible for the most commonly used range of electron energies in radiotherapy, being close to 0.5% at most depths and high-energies (see figure 2). The small change is justified in terms of the lack of ambiguity in the corrections used and higher accuracy of the present set of data. It is interesting to note that if the comparison is made with Sternheimer-based electron stopping-powers, differences would be larger at shallow depths (up to -1.0 % for most energies) and slightly smaller at depths beyond 0.2 r_0.

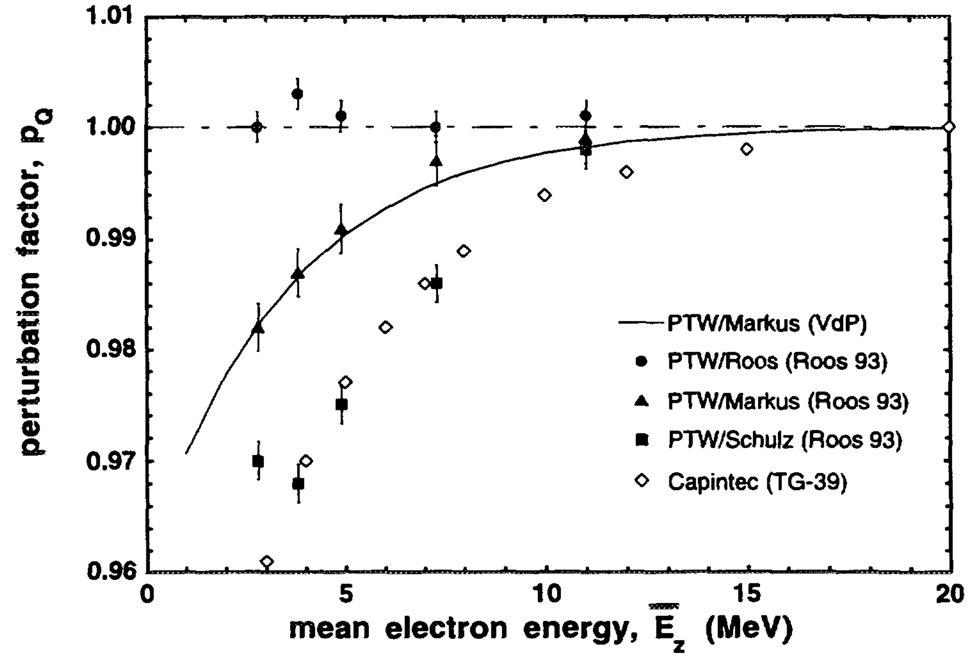

FIG. 1. The variation of the perturbation factor p_Q for several different plane-parallel chambers in common use, relative to the NACP chamber, indicated by the dashed line drawn at p_Q = 1.00. All the measurements were made at the depth of dose maximum and normalized to the quotient test chamber/NACP in a high-energy electron beam. The full line is a fit to 3 separate measurement series on different accelerators using the PTW/Markus chamber [37]. *The filled data points are measurements on three different PTW designs taken from* [38], *and re-normalized so that p_Q = 1 for the NACP chamber; the unfilled symbols are for the Capintec-PS-033 chamber as given in* [14].

As already mentioned, the specification of the "quality" of the electron beam in terms of the mean electron energy at the phantom surface is based on the "2.33 approximation", and stopping-power ratios selected with $s_{w,air}(E_o,z)$ using data from monoenergetic beams. The validity of these two approximations and their limitations is discussed in detail in Appendix B. In particular the influence of electron and photon contamination is demonstrated, showing maximum discrepancies up to 1% at z_{ref} between the $s_{w,air}(E_o,z)$ method and full Monte Carlo simulations. Differences are usually larger at shallow depths due to the difference in slope of the $s_{w,air}(z)$ distributions obtained with the two methods and increase further if analytic expressions yielding $\bar{E}_O$ values larger than the "2.33 approximation" are used [3].

It is emphasized that no accurate method exists today to predict the $s_{w,air}(z)$ dependence on the contamination of the beam unless a full Monte Carlo simulation of the complete accelerator treatment head is performed. On the other hand, the appendix on stopping-power ratios also describes two new methods recently proposed that, used in combination, could perhaps overcome the limitations described above.

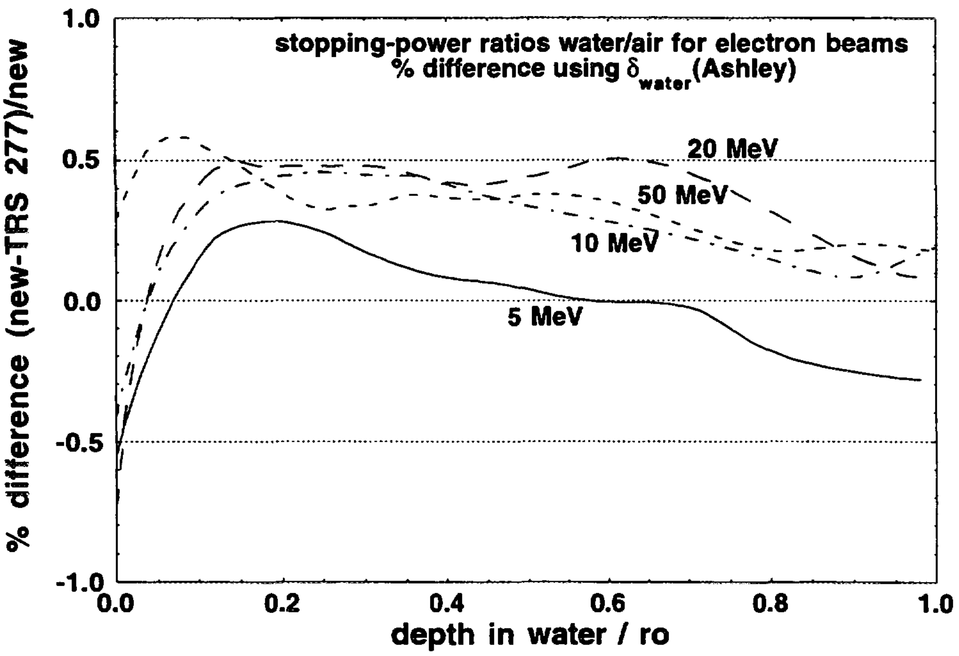

FIG. 2. Percent difference between the new stopping-power ratios for electron beams, $s_{w,air}$, given in Table III and those tabulated by TRS-277 [1] and other dosimetry protocols.

2.4.2. Non-reference conditions

Emphasis is given to the use of plane-parallel ionization chambers in non-reference conditions, especially to determine relative dose distributions.

For electron beams the need to take into account the depth variation of different quantities and correction factors for ion chamber measurements is stressed. This is a significant disadvantage compared with other detectors like TLD, diodes, plastic scintillators, synthetic diamonds, Fricke dosimeters or liquid ion chambers.

A common mistake in the application of TRS-277 for field sizes smaller than the reference field is to determine R_{50} for such fields and use equation (2) or alternative tables to determine $\bar{E}_O$, and then use $s_{w,air}(E_o,z)$ to select stopping-power ratios. As in TRS-277 it should be emphasized here that the validity of equations (2-4) or alternative tables is restricted to large field sizes. Users

TABLE II. SPENCER-ATTIX STOPPING-POWER RATIOS (Δ=10 KeV), WATER TO AIR ($s_{w,air}$) FOR ELECTRON BEAMS AS A FUNCTION OF $\bar{E}_0$ AND DEPTH IN WATER. Density effect correction (δ_{Ashley}) and I-values from ICRU-37 and electron fluence Monte Carlo calculations from Andreo [39] using the EGS4 Monte Carlo system.

depth in water(mm)	Electron beam energy $\bar{E}_0$																			
	1 MeV	2 MeV	3 MeV	4 MeV	5 MeV	6 MeV	7 MeV	8 MeV	9 MeV	10 MeV	12 MeV	14 MeV	16 MeV	18 MeV	20 MeV	22 MeV	25 MeV	30 MeV	40 MeV	50 MeV
R_p (mm)*	3.6	8.8	14.0	19.1	24.3	29.4	34.5	39.6	44.7	49.8	59.9	69.9	79.9	89.8	99.6	109.3	123.8	147.7	194.1	238.8
0	1.117	1.088	1.066	1.049	1.034	1.026	1.014	1.006	0.998	0.993	0.981	0.969	0.961	0.955	0.948	0.943	0.936	0.924	0.912	0.907
1	1.125	1.096	1.072	1.055	1.040	1.030	1.018	1.010	1.002	0.996	0.985	0.973	0.965	0.959	0.951	0.946	0.938	0.927	0.914	0.908
2	1.131	1.104	1.079	1.060	1.045	1.033	1.022	1.014	1.005	0.999	0.988	0.976	0.968	0.962	0.954	0.948	0.941	0.929	0.915	0.909
3	1.134	1.111	1.085	1.065	1.049	1.037	1.026	1.018	1.009	1.002	0.990	0.979	0.971	0.964	0.957	0.951	0.943	0.932	0.917	0.911
4	1.136	1.117	1.091	1.070	1.053	1.041	1.029	1.021	1.011	1.005	0.993	0.982	0.973	0.966	0.959	0.953	0.945	0.934	0.918	0.912
5		1.123	1.097	1.075	1.057	1.044	1.032	1.023	1.014	1.007	0.995	0.984	0.975	0.968	0.961	0.955	0.946	0.935	0.920	0.913
6		1.127	1.102	1.079	1.061	1.048	1.035	1.026	1.016	1.009	0.997	0.986	0.977	0.970	0.963	0.957	0.948	0.937	0.921	0.914
8		1.132	1.112	1.089	1.069	1.055	1.041	1.031	1.021	1.013	1.001	0.989	0.980	0.973	0.966	0.960	0.951	0.940	0.924	0.916
10		1.135	1.120	1.098	1.077	1.062	1.047	1.036	1.025	1.018	1.004	0.992	0.983	0.975	0.969	0.962	0.953	0.943	0.926	0.918
12			1.127	1.107	1.086	1.070	1.054	1.042	1.030	1.022	1.008	0.995	0.985	0.978	0.971	0.964	0.956	0.945	0.928	0.920
14			1.132	1.116	1.095	1.079	1.061	1.048	1.035	1.027	1.011	0.998	0.988	0.981	0.973	0.966	0.958	0.947	0.930	0.922
16			1.135	1.123	1.104	1.087	1.069	1.054	1.041	1.031	1.015	1.001	0.991	0.983	0.975	0.969	0.960	0.948	0.932	0.923
18			1.137	1.129	1.112	1.095	1.076	1.061	1.047	1.037	1.018	1.004	0.994	0.986	0.977	0.971	0.962	0.950	0.933	0.924
20				1.133	1.118	1.103	1.084	1.068	1.053	1.042	1.023	1.008	0.997	0.988	0.980	0.973	0.964	0.952	0.935	0.925
25					1.128	1.120	1.102	1.086	1.069	1.056	1.034	1.016	1.004	0.994	0.986	0.978	0.969	0.956	0.938	0.928
30					1.133	1.131	1.118	1.103	1.086	1.072	1.047	1.027	1.012	1.002	0.992	0.984	0.974	0.960	0.941	0.931
35						1.132	1.129	1.118	1.102	1.087	1.060	1.038	1.021	1.008	0.998	0.989	0.978	0.964	0.944	0.933
40								1.128	1.116	1.103	1.074	1.050	1.031	1.016	1.005	0.996	0.984	0.969	0.948	0.935
45								1.130	1.127	1.115	1.088	1.062	1.041	1.026	1.012	1.002	0.990	0.973	0.951	0.938
50										1.125	1.102	1.075	1.053	1.035	1.021	1.009	0.995	0.978	0.955	0.940
55										1.127	1.114	1.088	1.065	1.045	1.029	1.016	1.001	0.983	0.959	0.943
60										1.124	1.123	1.100	1.077	1.056	1.038	1.024	1.007	0.987	0.962	0.946
70											1.122	1.120	1.099	1.078	1.058	1.041	1.021	0.998	0.969	0.952
80												1.118	1.118	1.099	1.078	1.060	1.037	1.009	0.977	0.957
90													1.114	1.116	1.099	1.079	1.053	1.022	0.984	0.963
100															1.114	1.098	1.071	1.036	0.993	0.970
120																1.109	1.104	1.065	1.012	0.984
140																		1.095	1.034	0.999
160																		1.099	1.058	1.015
180																			1.081	1.033
200																			1.091	1.053
220																				1.071
240																				1.084

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* $R_p = -1.65 + 5.23\ E_p - 0.0084\ E_p^2$, average from Monte Carlo calculations for monoenergetic electrons using the EGS4 and ITS3 systems

should be aware that stopping-power ratios are almost independent of field size, see Figure 3, and using the incorrect approach just described to determine $\bar{E}_0$ will result in stopping-power ratios that correspond to a beam with a different energy.

In photon beams, plane-parallel ionization chambers are not recommended for absolute determinations, but for relative measurements on the central axis only and for output factors. Perturbation factors in photon beams are very sensitive to the details of the construction of a chamber and they cannot be predicted with an acceptable uncertainty. Furthermore, small changes from chamber to chamber in the manufacturing process render invalid the use of "general" factors for chambers of the same make. Plane-parallel ionization chambers should be avoided in very narrow beams such as those used in stereotactic procedures.

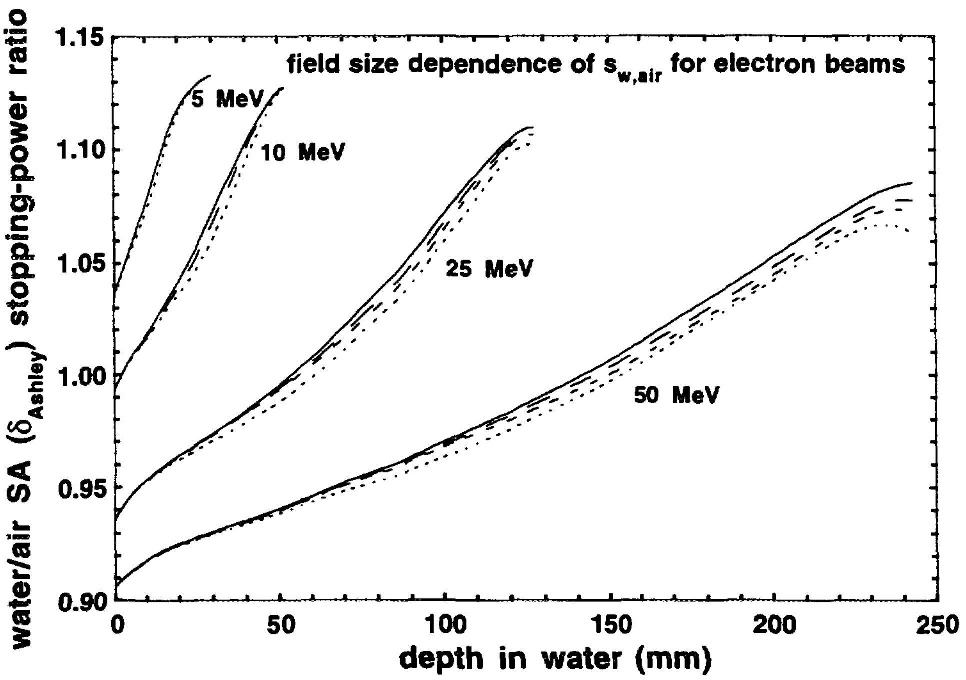

FIG. 3. Field-size dependence of water/air stopping-power ratios for electron beams determined with Monte-Carlo calculations. Radii shown in the figure are: for 5 MeV, 10 mm and broad beam; for 10 MeV, 10 mm, 20 mm and broad beam; for 25 MeV, 10 mm, 30 mm, 50 mm and broad beam; for 50 MeV, 10 mm, 40 mm, 60 mm and broad beam. The solid curves pertain to the broad beams.

3. TESTING OF THE NEW CODE

Tests at two different levels have been proposed to the IAEA by the working group:

- Category A - for checking that the Code is clearly written so that the procedure can be unambiguously carried out from a practical point of view. A comparison with absorbed dose determinations using TRS-277 will be included in this category. The group includes the (obvious) α-test by the authors followed by β–tests performed by independent persons. This category must be carried out before the new Code is published and it should not take more than two months. It should be undertaken by hospital physicists in several centres, some of which should not be in an English-speaking country.

- Category B - for testing that the correct absorbed dose to water is obtained by following the new Code of Practice. This category is a longer term project and represents a significant research project to be undertaken in a sophisticated centre or centres.

4. CONCLUSIONS

The forthcoming IAEA Code of Practice for plane-parallel ionization chambers should improve the accuracy of electron beam dosimetry and, to a lesser extent, of photon beam dosimetry too. Whereas efforts are being made to implement the latest developments in ionization chamber dosimetry, the verification of the Code will show if they are to be preferred to previous methods or to procedures recommended in other recent protocols in the same field. It is hoped that changes in structure, compared with TRS-277, will facilitate the use of the Code.

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