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Electron Beams with Mean Energies at the Phantom Surface below 15 MeV

Supplement to the Recommendations by
the Nordic Association of Clinical Physics (NACP) 1980

These recommendations have been produced by the Nordic Association of Clinical Physics. The members of the task group were: Hans Svensson (chairman), Alan Nahum (secretary), Klaus Ennow, Lars Olof Mattsson and Niels Ulsø. Valuable criticism from A. Brahme, K.-A. Johansson, H. Järvinen and L. Lindborg is gratefully acknowledged.

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These supplementary recommendations are also published together with the NACP (1980) recommendations as Supplement 364 to Acta Radiologica.

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Introduction

The Nordic Association of Clinical Physics (NACP) published general recommendations for absorbed dose determination in electron and photon beams with maximum energies between 1 and 50 MeV in 1980. It was stated there that a supplement would be published, whose main purpose would be to recommend procedures for measurements in electron beams of energies below about 10 MeV. The supplement would, in addition, contain more recent values of stopping power ratios for electron beams. This supplement is now presented and is to be used in conjunction with the previous recommendations (NACP 1980). Tables 1 to 8, figures 1 to 8 and equations 1 to 11 are consequently to be found in the main document.

NACP (1980) recommended that a cylindrical ionization chamber be used for determinations of absorbed dose at all qualities except for low electron energies. It was pointed out that for such beam qualities the cylindrical chambers generally in use were unsuitable as they produce an unacceptably large perturbation of the electron fluence at the point of interest. A plane-parallel ionization chamber was recommended for this situation but the measurement procedures were not dealt with as sufficient experimental data were not then available. Therefore, a comprehensive investigation has been carried out, initiated by the Swedish National Institute of Radiation Protection (SSI), to determine the necessary physical data to be used with a plane-parallel chamber (MATTSSON et coll. 1981). As a result of this work, a procedure for absorbed dose determination at mean electron energies at the phantom surface, $\bar{E}_0$, below 15 MeV can now be recommended.

A major revision of stopping-power ratios has recently been carried out by BERGER & SELTZER (1982). These are the best available data and consequently are recommended here. The difference in stopping-power ratios $(s_{\mathrm{w,air}})_{\mathrm{u}}$ for electron beams compared with those given in NACP (1980) is never more than 1.5 per cent for all energies ($\bar{E}_0$) and all phantom depths. The values of k_{m} are affected by the new stopping-power ratio data but the change is negligible for graphite and only 0.6 per cent for A-150 (cf. Table 4 in NACP 1980). In the case of photon beams both the stopping-power ratio $(s_{\mathrm{w,air}})_{\mathrm{u}}$ and the factor $p_{\mathrm{u,wall}}$ are affected. However, the product $(s_{\mathrm{w,air}})_{\mathrm{u}}\, p_{\mathrm{u,wall}}$ (and hence the value obtained for the absorbed dose) changes by only 0.5 per cent at most (NAHUM 1982).

Plane-parallel ionization chamber

Several authors have described the construction and performance of plane-parallel chambers for the determination of absorbed dose in electron beams (RASE & POHLIT 1962, MORRIS & OWEN 1975, MARKUS 1976, HOLT et coll. 1979, MATTSSON et coll. 1981). A plane-parallel chamber should have a cavity which is small in the beam direction and a guard ring of such a width that the perturbation due to the in-scattering effect (cf. Fig. 9 and HARDER 1968, 1974) is insignificant even if low energy electrons are used. A cavity with a thickness of about 2 mm and a collecting electrode with a diameter between 5 and 20 mm in combination with a guard ring of at least 3 mm in width has been demonstrated to have suitable dimensions (MATTSSON et coll. 1981). For such chambers if the front surface of the air cavity is taken as the effective point of measurement then the perturbation factor $p_{\mathrm{u,pp}} = 1.000 \pm 0.005$ (MORRIS & OWEN, MARKUS).

A plane-parallel chamber must be designed so that it does not have a large polarity effect, i.e. for a given irradiation the absolute value of the collected charge should be independent of the polarity on the high voltage electrode of the chamber. The polarity effect depends on the depth of the chamber in the phantom and may be of different signs at small and large depths. It is due to a lack of equilibrium in the charge transport, i.e. the number of the electrons entering and leaving a small volume at the point of interest in the medium may differ (cf. VAN DYK & MACDONALD 1972). The polarity effect can be minimized by making the collecting electrode and the insulating layer thin compared with thickness of the air volume (Fig. 10). The cable may also contribute to the effect and this may need to be investigated.

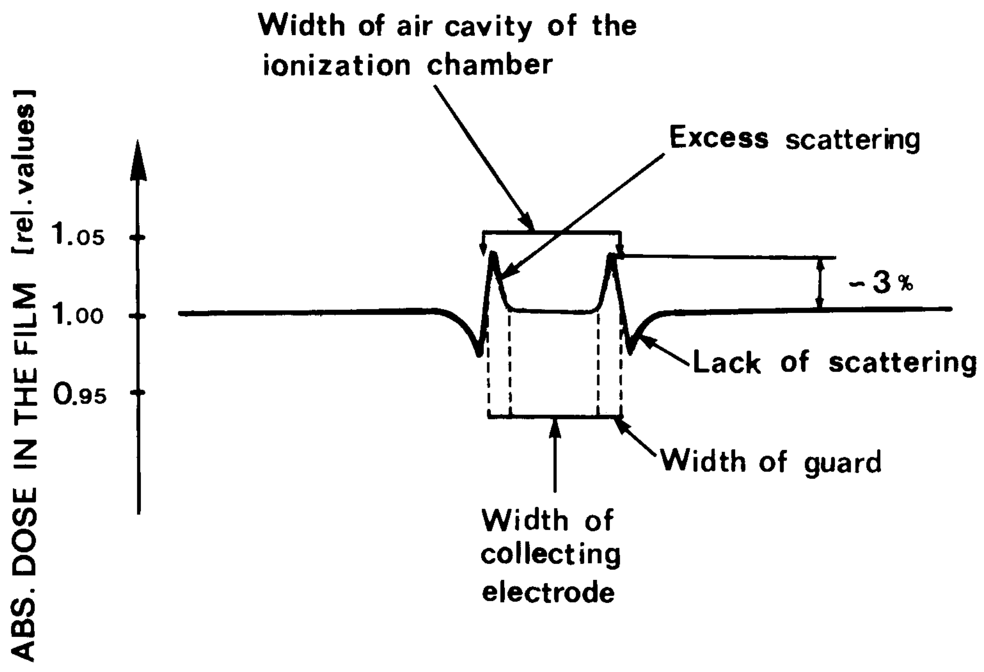

Fig. 9. Measurement of the in-scattering from the side-walls of a coin-shaped cavity. The air-gap was 2 mm and the diameter of the collecting electrode 10 mm. The measurements were carried out at $\bar{E}_0=6$ MeV with the front surface of the cavity at the dose maximum (5 mm depth) in PMMA (MATTSSON et coll. 1981; SVENSSON & NAHUM 1981). The perturbation of the electron fluence (and hence absorbed dose) does not extend into the sensitive region of the air volume if the guard is wide enough. The electron fluence in the sensitive air volume is then the same as that entering through the front surface of the cavity (assuming negligible inverse square law effect). Hence this is where the effective point of measurement is situated.

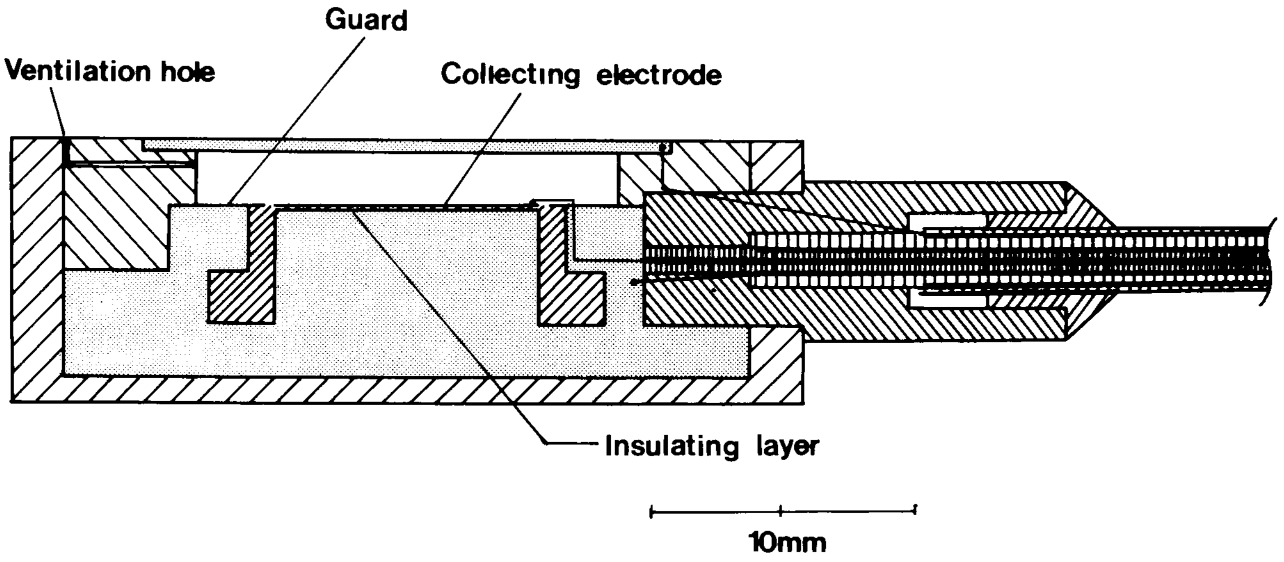

Fig. 10. A design for a plane-parallel chamber (the 'NACP chamber') which follows the specifications set out in this protocol. The very narrow (2 mm) air gap and the presence of the guard ring minimize perturbation effects. The collecting electrode is very thin (<0.1 mm) and is mounted on a thin insulating layer (≈0.2 mm) in order to give a negligible polarity effect. The front wall (0.5 mm thick to enable measurements to be made at small depths) and back wall are made of one single material (in this case graphite). ▨ ▨ Rexolite. ▦ Graphite.

The polarity effect will generally increase with decreasing electron energy. The effect varies depending on the shape of the absorbed dose distribution, being largest for a monoenergetic and monodirectional beam as the primary electrons are then stopped in a very narrow depth-region. The magnitude of the effect can be determined for given irradiation conditions as the ratio

Table 9

Properties of a plane-parallel chamber for it to be acceptable for use with this protocol

Chamber property	Specification
Guard ring	Width sufficient to make $p_{u,pp} \approx$ 1.000 (e.g. 3 mm width for 2 mm cavity thickness)
Polarity effect	$(\lvert Q_+\rvert - \lvert Q_-\rvert)/(\lvert Q_+\rvert + \lvert Q_-\rvert) \leq 0.005$ at all depths and energies
Wall material (if different from phantom material)	Approximately tissue-, water-, or air-equivalent, provided that front wall thickness ≤0.5 mm

Table 10

The factor h_m for use in eq. (15) (MATTSSON et coll. 1981); h_m is defined as the ratio of the signal measured at the ionization maximum on the central axis in a water phantom to that measured for the same accelerator monitor setting at the ionization maximum in other phantom materials. h_m is independent of $\bar{E}_0$ (between 2 and 14 MeV) within the limits of the stated uncertainty

Phantom material	h_m
PMMA	1.000±0.003
Polystyrene	1.006±0.004
A-150	1.006±0.003

$(\lvert Q_+\rvert - \lvert Q_-\rvert)/(\lvert Q_+\rvert + \lvert Q_-\rvert)$ where Q_+ and Q_- are the signals (charge) measured with a change in sign of the polarizing voltage only. Such ratios should be determined at the lowest electron energy in use at the department at a number of depths from the surface region down to the beginning of the rapid fall-off part of the depth–dose curve. The first few measurements made with the chamber after inverting the collecting voltage should be disregarded; several measurements have to be carried out to ensure stable and reproducible values. The absolute value of the ratio $(\lvert Q_+\rvert - \lvert Q_-\rvert)/(\lvert Q_+\rvert + \lvert Q_-\rvert)$ should never be greater than 0.005. The corrected value of the charge is given by $(\lvert Q_+\rvert + \lvert Q_-\rvert)/2$.

The short- and long-term reproducibility for a plane-parallel chamber is often less good than for a cylindrical chamber (MATTSSON et coll. 1981). However, the chamber should have a long-term reproducibility within ±0.5 per cent.

Cylindrical chambers of either 0.5 mm graphite or A-150 walls were recommended in NACP (1980). The reasons were that the values of the correction factors introduced in the calibration of the chamber at ^{60}Co (i.e. to derive N_D) and in the measurements in other photon beams are critically dependent on the composition and thickness of the chamber wall and that these factors were known for these types of walls. The factor k_{pp} required when the plane-parallel chamber is calibrated in a ^{60}Co beam (alternative B, page 409) can also be expected to be dependent on the chamber wall material. This factor has only been determined for the 'NACP chamber', which has a 0.5 mm graphite front wall (Fig. 10).

For plane-parallel chambers that are calibrated in a high-energy electron beam (alternative A, page 409) the front and back walls may be made of any material of known composition that is approximately tissue-, water- or air-equivalent with respect to electron slowing-down (i.e. the mean ionization potential should be between 60 and 90 eV) provided that the front wall is thin, i.e. not more than about 0.5 mm thick. The properties that a plane-parallel chamber should have in order to be acceptable for use with this protocol are summarized in Table 9.

Phantom

The accelerator dose monitor is generally calibrated to give the absorbed dose to water at the dose maximum in a water phantom. This is a generally accepted procedure in spite of the fact that the absorbed dose to tissue may differ by a few per cent from that to water. In NACP (1980) it was recommended that the measurements be carried out in a water phantom. Ideally, this recommendation also applies for a plane-parallel chamber. However, it is often more practical to use a plastic phantom, especially at energies below 5 MeV, where measurements in water are almost impossible. If the measurements are made in plastic, conversion factors must be applied in order to obtain the absorbed dose to water. Table 10 gives the ratio, h_m, of the signal measured at the ionization maximum on the central axis in a water phantom to that measured for the same accelerator monitor setting at the ionization maximum in other phantom materials.

For PMMA (polymethyl methacrylate—Perspex,

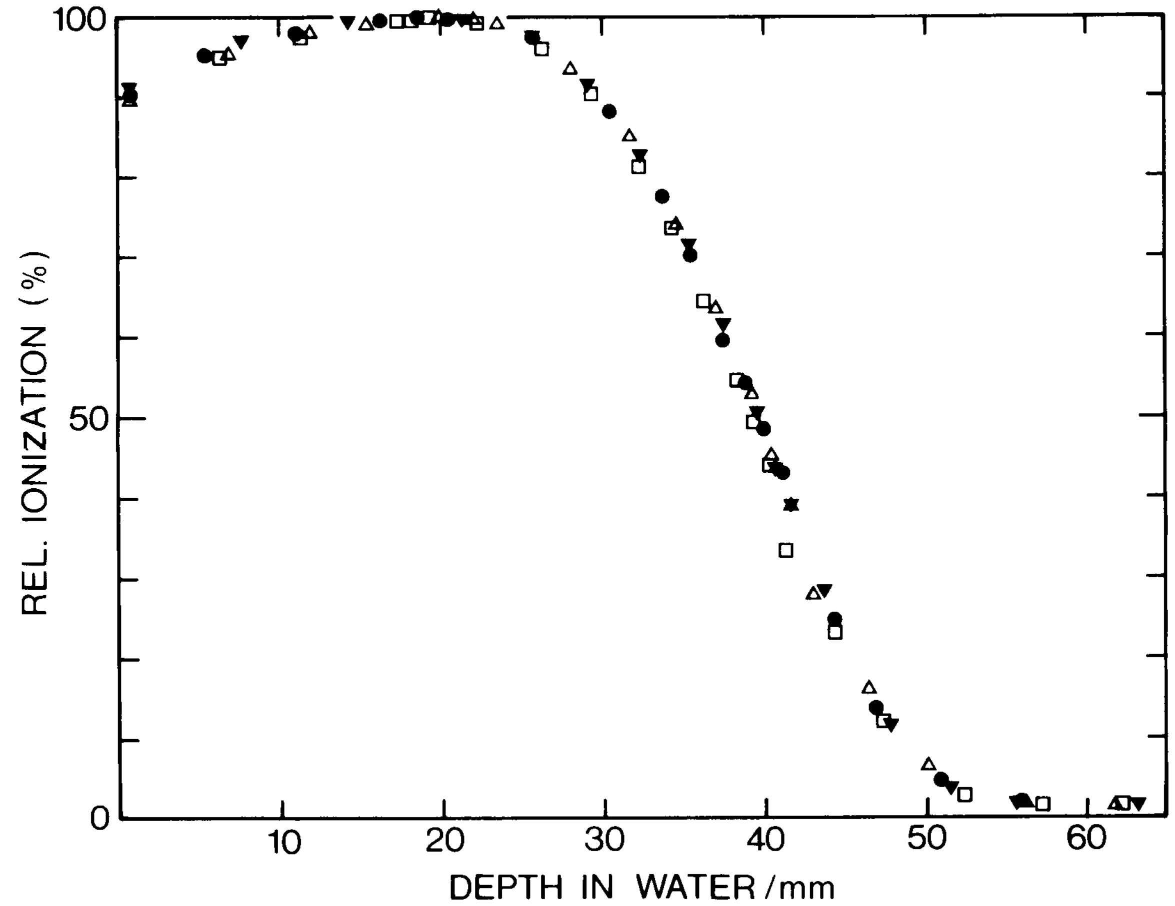

Fig. 11. Comparison of depth ionization curves measured in various phantom materials (MATTSSON et coll. 1981). All curves are normalized at the maximum ionization values. They have been converted to depth in water using eq. (14) with the b_m-values from Table 2 (NACP 1980). Measured in water (□), Polystyrene (●), PMMA (△) and A-150 (▼).

Lucite, Plexiglas), h_m is equal to 1.000±0.003, and the ionization values for polystyrene and A-150 are lower than for water (Table 10). Measurements with a plane-parallel chamber can thus be made in a plastic phantom and converted into an ionization value for the dose maximum in water.

It may also be convenient to measure the complete depth–ionization curve in a plastic material and make a conversion to a corresponding curve in water. Below about 15 MeV such a re-calculation is straight-forward as a simple scaling of the curve from plastic to water may be made. NACP (1980) gave a relation (eq. 4 and Table 2) which can be written:

$$R_{p,w} = b_m R_{p,m} \qquad (4)$$

where $R_{p,w}$ is the practical range measured in water and $R_{p,m}$ in the phantom material. The symbol b_m replaces k used in eq. (4) in NACP (1980). This is in order to avoid any confusion with k_{att}, k_m, and k_{pp}. Furthermore, m replaces pl and w replaces H_2O as subscripts. It has been shown that eq. (4) is also a good approximation for other depths on the depth-ionization curves for energies below about 15 MeV and field sizes larger than 8 cm × 8 cm (Fig. 11 and MATTSSON et coll. 1981). The largest deviation between depthi–onization curves measured in water and those converted from measurements in plastic is obtained at depths approximately corresponding to R_{85}. The R_{85} for water converted from measurements in polystyrene may in the worst case give an overestimate of up to 3 mm; this is the case for a very 'clean' beam (BRAHME et coll. 1975). Good agreement is obtained for range conversions made from measurements in PMMA, polystyrene or A-150. h_m is equal to 1.000±0.003 for PMMA, which is therefore the phantom material that is simplest to use. The procedure is valid for SSD ≥1 m (see NACP 1980).

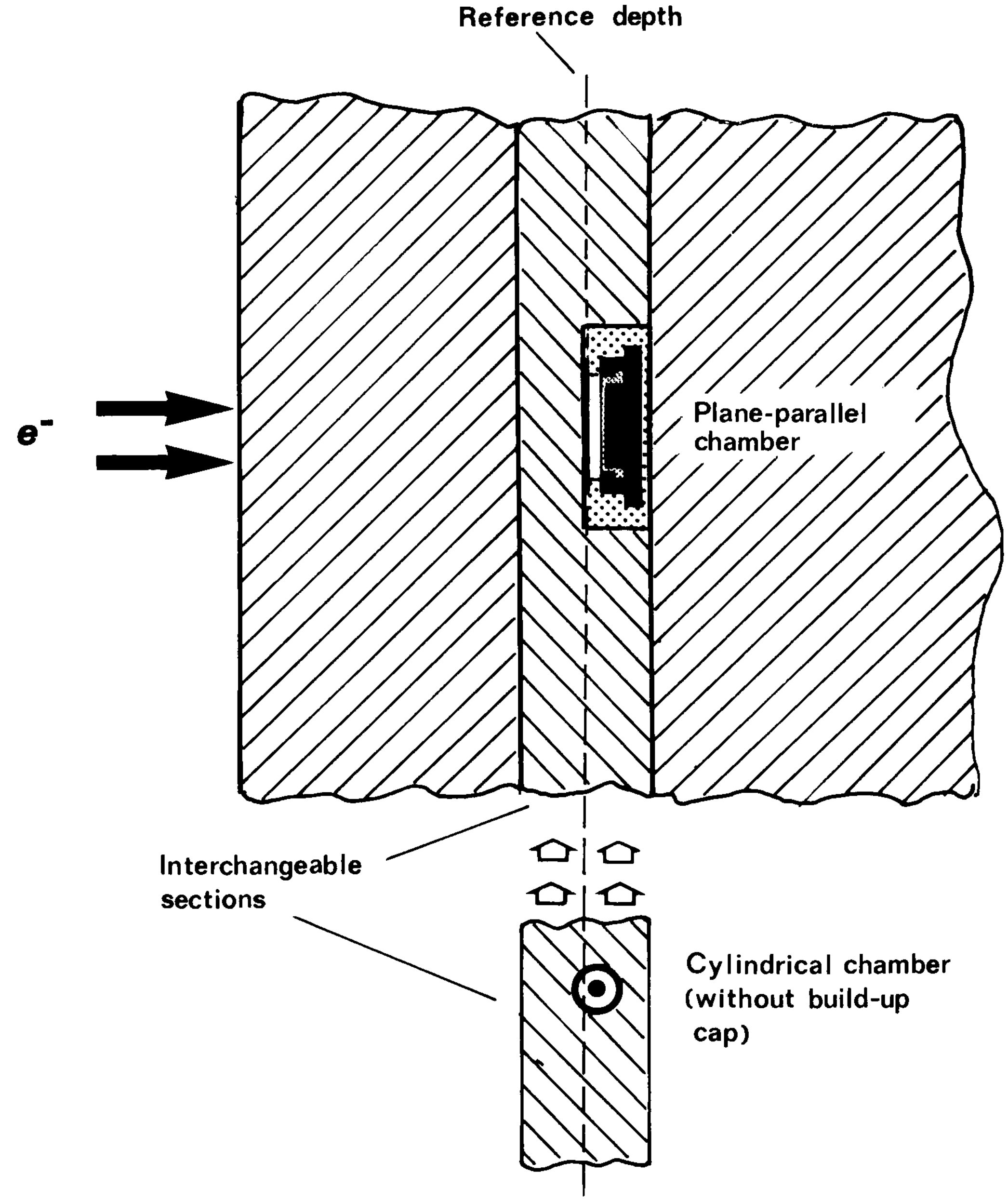

Fig. 12. The irradiation geometry for calibration in a high-energy electron beam ($\bar{E}_0 \geqslant 18$ MeV, field $\geqslant 12$ cm × 12 cm at phantom surface, SSD 1 m; cf. alternative A). The absorbed dose to air ionization chamber factor $N_{D,\,\mathrm{pp}}$ for a plane-parallel chamber can be determined from a comparison in an electron beam ($\bar{E}_0 \geqslant 18$ MeV) with a cylindrical chamber with known $N_{D,\,\mathrm{cyl}}$-factor. The cylindrical and the plane-parallel chamber (i.e. their effective points of measurement) have to be placed at the reference point.

Energy determination

NACP (1980) gives a full description of the methods to be used for energy determination. The mean energy at the phantom surface, $\bar{E}_0$, is recommended as an input parameter for dosimetric constants determined from eq. 3 and Fig. 3. This equation is valid for energies $\bar{E}_0$ above 5 MeV. Below this energy the most probable energy, $E_{\mathrm{p},0}$, can be determined from the practical range in water, R_p, using eq. (2). At these low energies the difference between $E_{\mathrm{p},0}$ and $\bar{E}_0$ should be insignificant for practical purposes; this is due to the small thickness of scattering foils needed in the beam at these energies to obtain uniform fields. If the practical range has been determined in PMMA then eq. (4) in NACP (1980) has to be used to convert to ranges in water.

Table 11

Perturbation correction factors for cylindrical ionization chambers, $p_{u,cyl}$. These factors are used for the determination of $N_{D,pp}$ (in eq. 12) by interpolation. $\bar{E}_z$ is an approximate value for the mean energy at the dose maximum. The values are derived from JOHANSSON *et coll. (1978)*

$\bar{E}_z$/MeV	Internal chamber radius		
	1.5 mm	2.5 mm	3.5 mm
22	0.999	0.998	0.997
20	0.997	0.995	0.994
15	0.995	0.992	0.989
12	0.993	0.988	0.984

Determination of absorbed dose to air ionization chamber factor

Calibration of the plane-parallel chamber

In order to be able to determine the absorbed dose using eq. (11), the absorbed dose to air ionization chamber factor, N_D, must be known for the plane-parallel chamber. Two different methods of carrying out the determination of the N_D factor are recommended:

A. *Comparison against a thimble chamber with known N_D in a high-energy electron beam.* This method is recommended for those radiation therapy departments which have therapy machines that produce electron beams with mean energies at the phantom surface ($\bar{E}_0$) of at least 18 MeV. Such centres will already have a thimble chamber with a known N_D factor, usually determined by the national standards laboratories. This method is the only possible alternative for a plane-parallel chamber for which k_{pp} (cf. alternative B) is not accurately known.

The calibrated thimble chamber (local reference chamber) and the plane-parallel chamber are irradiated at or near the reference point in the PMMA phantom in the high-energy electron beam (cf. eq. 14 for the determination of the depth of the reference point in PMMA). The chambers should be irradiated one at a time with their effective points of measurement (cf. page 71 in NACP 1980 and Fig. 9) at the same depth. The irradiation geometry is shown in Fig. 12. The use of an external monitor is recommended in addition to the accelerator monitor. The field size should be at least 12 cm × 12 cm at the phantom surface.

It is required that the plane-parallel chamber measures the same absorbed dose in PMMA (or water) as the air kerma-calibrated thimble chamber. $N_{D,\mathrm{pp}}$ is then obtained from

$$N_{D,\mathrm{pp}} = \frac{M_{\mathrm{cyl}} N_{D,\mathrm{cyl}} p_{\mathrm{u,cyl}}}{M_{\mathrm{pp}} p_{\mathrm{u,pp}}} \tag{12}$$

where M_{cyl} and M_{pp} are the meter readings for the thimble and plane-parallel chambers, respectively, for the same absorbed dose to the phantom, corrected for recombination losses and if necessary to the same temperature, pressure etc. $p_{\mathrm{u,cyl}}$ is given in Table 11; this factor is known with sufficient accuracy for the high-energy electron beams recommended. The value of $p_{\mathrm{u,pp}}$ can be set equal to 1.000 for plane-parallel chambers that fulfill the conditions specified in this protocol.

B. *Calibration in a ^{60}Co gamma beam.* The national standards laboratories in the Nordic countries base their calibration services on the known exposure rate, free in air, at a distance of 1 m and a field size of 10 cm×10 cm; the air kerma rate, $\dot{K}_{\mathrm{air,c}}$ is then calculated according to eq. (5) in NACP (1980). The present procedure will make use of this knowledge of $\dot{K}_{\mathrm{air,c}}$ to derive $N_{D,\mathrm{pp}}$ for the plane parallel chamber. It is strongly recommended that if the plane-parallel chamber is calibrated in a ^{60}Co beam, then this should be done at the national standards laboratory in order to reduce the uncertainty. Other procedures to determine $N_{D,\mathrm{pp}}$ may also be used at the standards laboratories; however, this will not influence the method of determining the absorbed dose in the electron beam.

In principle the calibration of the plane-parallel chamber could be made free in air as with cylindrical chambers (MATTSSON et coll. 1981). However, a more practical procedure has turned out to be a calibration in a PMMA phantom. The size of this phantom should be at least 15 cm × 15 cm × 15 cm and it should have a build-up layer of 4 mm PMMA (Fig. 13).

The plane-parallel chamber is positioned so that the centre of its air cavity is at the point where $\dot{K}_{\mathrm{air,c}}$ is known. The air kerma calibration factor, $N_{K,\mathrm{pp}}$, for the chamber with the phantom irradiated in this geometry (Fig. 13) is

$$N_{K,\mathrm{pp}} = \frac{\dot{K}_{\mathrm{air,c}}}{\dot{M}_{\mathrm{pp}}}$$

where $\dot{M}_{\mathrm{pp}}$ is the meter reading, in C or scale divisions, per unit time, corrected for temperature, pressure and recombination.

The absorbed dose to air ionization chamber factor for the plane-parallel chamber, $N_{D,\mathrm{pp}}$, is then given by

$$N_{D,\mathrm{pp}} = \frac{\dot{D}_{\mathrm{air,c}}}{\dot{M}_{\mathrm{pp}}} = N_{K,\mathrm{pp}}(1-g)k_{\mathrm{pp}} \qquad (13)$$

where the factor k_{pp} has been experimentally determined by MATTSSON et coll. (1981) for the plane-parallel chamber shown in Fig. 10. The value of k_{pp} is equal to 0.996 for this chamber irradiated in the geometry shown in Fig. 13.

The factor k_{pp} is defined by $\dot{D}_{\mathrm{air,c}} = \dot{K}_{\mathrm{air,c}}(1-g)k_{\mathrm{pp}}$ (cf. eq. 7 in NACP 1980) for the irradiation geometry in Fig. 13. It is thus analogous to $k_{\mathrm{att}}k_{\mathrm{m}}$ for the thimble chamber plus build-up cap, but also includes a component to allow for backscatter from the phantom material behind the chamber. It is possible in principle to calculate the value of k_{pp} from theory but this represents a difficult and complicated problem. Instead, k_{pp} was derived from a determination of $N_{D,\mathrm{pp}}$ in a high-energy electron beam using a thimble chamber with a known $N_{D,\mathrm{cyl}}$ factor; the plane-parallel chamber and the thimble chamber were required to yield the same value for absorbed dose to water at the reference depth (cf. alternative A).

It should be pointed out that the procedure described under B can only be used for the type of chamber shown in Fig. 10, as the correction factor k_{pp} is not accurately known for other chambers.

Periodic calibration and consistency control

The reproducibility of the plane-parallel chamber is often not as good as for a cylindrical chamber due to the thinness of the front wall and the air volume. It is therefore recommended that the response of the chamber be periodically checked in a fixed irradiation geometry either in a beam from a known isotope, or by using a cylindrical chamber as a monitor; the PMMA phantom is suitable for this purpose. It is essential that a consistency check is performed before and after the plane-parallel chamber is sent away for calibration. The plane-parallel chamber should be re-calibrated at least once every two years.

Certain centres may have the facilities to perform the determination of $N_{D,\mathrm{pp}}$ according to both method A, and method B based on the transfer of the air kerma calibration factor. In this case the centres are advised to use method B to check a calibration made according to method A, which is to be considered as the more fundamental method. Discrepancies of over one per cent should be reported to the national standards laboratory.

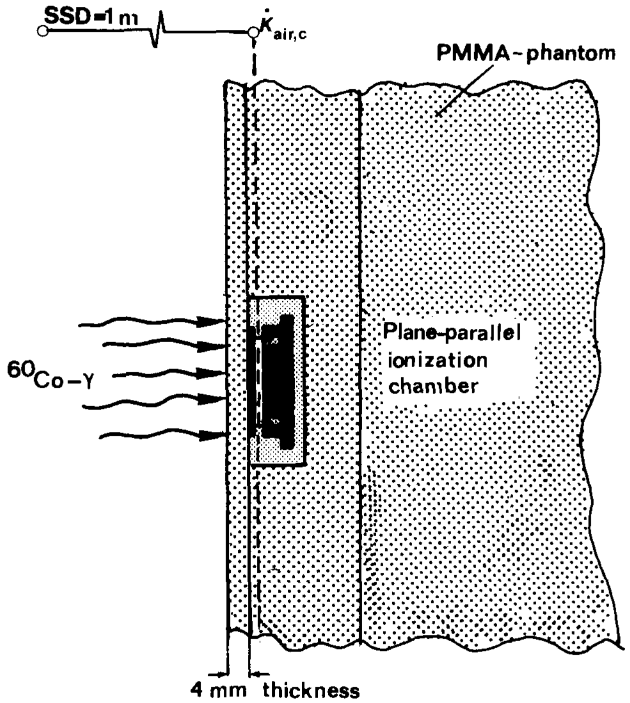

Fig. 13. The irradiation geometry for calibration in a known kerma rate in a ^{60}Co gamma ray beam (field = 10 cm × 10 cm at the depth of the chamber centre; cf. alternative B). A PMMA phantom is used for the determination of the factor $N_{D,\mathrm{pp}}$ for the plane-parallel chamber in the ^{60}Co-beam; the chamber is placed with its centre at the point where $\dot{K}_{\mathrm{air,c}}$ is known.

Absorbed dose determination in water

Determination at the reference point

The absorbed dose at the reference point in water is determined from an irradiation of the plane-parallel chamber in water or in a plastic phantom. If the measurements are performed in a plastic phantom then the depth in the phantom corresponding to the depth of the reference point in water (Table 3 in NACP 1980) is obtained from the relation

$$R_{100,\mathrm{w}} = R_{100,\mathrm{m}}\, b_{\mathrm{m}} \qquad (14)$$

where b_{m} is given in Table 2 (as k) in NACP (1980). These b_{m}-factors are valid for R_{100} as well as R_{p} (cf. page 407).

A factor h_m is required to correct for possible differences in the electron fluence at the dose maximum in water and in the plastic phantom. These factors have been determined for three suitable phantom materials—PMMA, polystyrene and A-150—and are reproduced here in Table 10. The meter reading that would have been obtained with the chamber at the dose maximum in a water phantom is given by

$$M_{u,w} = M_{u,m} h_m \qquad (15)$$

where $M_{u,m}$ is the meter reading at the user's quality u with the chamber inside a plastic phantom corrected for temperature, pressure, recombination etc. in C or scale divisions; h_m can be set equal to 1.000 for the PMMA phantom recommended here.

The chamber is positioned in the water or plastic phantom so that its effective point of measurement (front surface of the air cavity) is at the reference point. The absorbed dose at the reference point in water is then obtained from

$$D_{w,u} = N_{D,pp} M_{u,w} (s_{w,air})_u p_{u,pp} \qquad (16)$$

where $(s_{w,air})_u$ is the water to air mass stopping power ratio at the user's radiation quality for the depth $R_{100,w}$ (where this may have been calculated from $R_{100,PMMA}$ using eq. 14). Numerical values of $(s_{w,air})_u$ are given in Table 11 (cf. also the discussion on stopping-power ratios on page 69 in NACP 1980). For the type of plane-parallel chamber recommended here, $p_{u,pp}$ can be set equal to 1.000.

The absorbed dose determination carried out with the plane-parallel chamber must be confirmed with an independent dosimetric method before any irradiation of patients (cf. page 65 in NACP 1980). It is possible to use the plane-parallel chamber for $\bar{E}_0 \geqslant 15$ MeV but the cylindrical chamber is the main recommendation at these energies (NACP 1980).

Determination at any point

Beam axis absorbed dose distribution. A complete central axis depth-ionization curve can be determined using the plane-parallel chamber in water or in the plastic phantom. In the latter case this can then be converted into depth-ionization values in water using the h_m-values given in Table 10 and converting from depth in plastic to depth in water using eq. (14) (page 410, Fig. 11). It should be noted that the effective point of measurement is located at the depth of the inside of the front wall for a plane-parallel chamber. The conversion to a depth-absorbed dose distribution in water is then completed by inserting the appropriate value of $(s_{w,air})_u$ in eq. (16).

It is possible to use other dosimeter systems directly in water, e.g. semi-conductor detectors or liquid-ionization chambers and make measurements relative to the absorbed dose at the reference point. However, such dosimeters must have been checked against measurements with a plane-parallel ionization chamber in order to investigate any dependence due to the changing radiation quality at different depths in water (cf. page 73 in NACP 1980).

Iso-absorbed dose distribution. Isodose curves are most conveniently measured using semi-conductor detectors but such detectors should be checked for possible depth and energy dependence against measurements with a plane-parallel ionization chamber or a ferrous-sulphate dosimeter. Photographic film can be used to measure the absorbed dose at points outside the beam axis (cf. NACP 1980).

Absorbed dose measurement uncertainty

The overall uncertainty of the determination of the absorbed dose is a combination of the uncertainties resulting from the determination of the N_D factor for the chamber and the uncertainty in the stopping-power ratio $(s_{w,air})_u$ and the perturbation factor, $p_{u,pp}$, used to convert the product of the electrometer reading and N_D to absorbed dose in water. Some uncertainty is also involved in converting measurements in the plastic phantom to corresponding values in water, which is negligible for depths up to the dose maximum but increases at depths near the end of the electron range.

In order to check the complete procedure an extensive set of measurements has been carried out by MATTSSON et coll. (1982); the method described in the present protocol was compared with absorbed dose measurements with ferrous sulphate dosimeters. The measurements were carried out using different electron accelerators. It was concluded that the agreement in absorbed dose determination was better than one per cent in the dose maximum region. It is therefore realistic to expect that the spread in absorbed dose determinations between the departments which use this protocol should not exceed 3 per cent.

Appendix A — Numerical example

Determination of the absorbed dose to air ionization chamber factor

Electron beam with $\bar{E}_0 \geq 18$ MeV available at the radiation therapy centre. A cylindrical ionization chamber has been calibrated at one of the Nordic standards laboratories. The chamber has a graphite wall and a build-up cap of graphite with a total thickness of 0.45 g cm^{-2}. The chamber satisfies the requirements in NACP (1980). The calibration factor at ^{60}Co gamma has been determined as

$$N_{K,\mathrm{cyl}} \left(= \frac{K_{\mathrm{air,c}}}{M_\mathrm{c}} \right)$$

$$= 100.0 \text{ mGy nC}^{-1} \text{ at } 22.0°\text{C, } 101.33 \text{ kPa}$$

The absorbed dose to air ionization chamber factor, N_D, is derived from eq. (8) and Table 4:

$$N_{D,\mathrm{cyl}} = N_K(1-g)\,k_\mathrm{att}\,k_\mathrm{m}$$

$$N_{D,\mathrm{cyl}} = 100.0 \times (1-0.004) \times 0.990 \times 0.991$$
$$= 97.7 \text{ mGy nC}^{-1}$$

The cylindrical chamber is now to be used to determine $N_{D,\mathrm{pp}}$. The chamber is therefore placed in a PMMA phantom. The department has an electron accelerator which gives a maximum $\bar{E}_0 = 20$ MeV.

The reference depth is 3 cm in water for $\bar{E}_0 = 20$ MeV. This depth corresponds to 2.6 cm PMMA according to eq. (14). The exact depth is not critical but it is important that it is the same for the two chambers. The effective point of measurement of the chambers is to be placed at this depth which means that for the cylindrical chamber the centre of the chamber is to be placed at 2.75 cm depth as the chamber in this example has a radius of 0.3 cm. In the case of the plane-parallel chamber the front surface of the air cavity is to be placed at 2.6 cm depth.

Irradiations using a large field size (i.e. ≥12 cm × 12 cm) are now carried out with the centres of the chambers positioned on the central axis in succession. At least two sets of such measurements are performed. Both chambers are assumed to be at the same temperature and pressure. An external monitor is used in addition to the accelerator monitor.

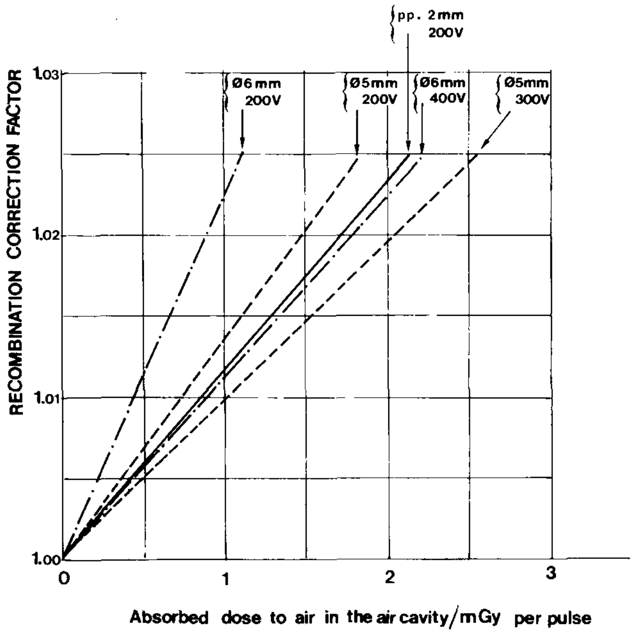

Fig. 14. Recombination correction factor for pulsed radiation for cylindrical chambers (internal diameters 5 mm or 6 mm with central electrode diameter 1 mm) and for a plane-parallel chamber with a 2 mm air gap—derived from information given by Boag (1966).

Corrections have to be carried out for recombination. Therefore the mean absorbed dose per pulse to the air inside the air cavity, $\bar{D}_\mathrm{air}$, must be determined; an approximate value is sufficient as the recombination correction is fairly small in most cases. Assuming that the meter reading is 20.00 nC when the cylindrical chamber is irradiated for 60 s and that a pulse repetition frequency of 50 Hz has been used the absorbed dose to air per pulse is

$$\bar{D}_\mathrm{air} \approx 20.00 \times 97.7/(60 \times 50) = 0.65 \text{ mGy}$$

The recombination correction for a cylindrical chamber of 6 mm cavity diameter and 1 mm inner electrode diameter is given in Fig. 14. For a collecting potential of 200 V this is equal to 1.015. Therefore the meter reading to be used in eq. (12) should be

$$M_{\mathrm{u,cyl}} = 20.00 \times 1.015 = 20.3 \text{ nC}$$

The plane-parallel chamber is now placed at the reference depth. An irradiation giving the same

Table 12

Recommended values of $(s_{w,air})_u$ as a function of depth z and mean energy at the phantom surface, $\bar{E}_0$, for electron radiation. The values are taken from Berger & Seltzer *(1982) with energy cut-off $\Delta = 10$ keV, I (water)=75.0 eV and I (air)= 85.7 eV. These values replace the calculations by* Berger *et coll. (1975). For $\bar{E}_0 > 16$ MeV the differences from Table 7 (NACP 1980) are negligible*

Depth z/mm	$\bar{E}_0$/MeV										Depth z/mm	$\bar{E}_0$/MeV		
	1	2	3	4	5	6	7	8	9	10		12	14	16
1	1.128	1.107	1.088	1.068	1.054	1.042	1.032	1.024	1.016	1.009	2	0.998	0.988	0.979
2	1.133	1.112	1.090	1.071	1.056	1.044	1.034	1.025	1.017	1.010	4	1.001	0.990	0.981
3	1.136	1.116	1.094	1.074	1.058	1.046	1.035	1.026	1.019	1.012	6	1.003	0.993	0.984
4	1.137	1.119	1.099	1.079	1.062	1.048	1.037	1.028	1.020	1.013	8	1.007	0.996	0.985
5		1.123	1.103	1.083	1.065	1.051	1.040	1.030	1.022	1.014	10	1.010	0.998	0.989
6		1.127	1.107	1.087	1.069	1.054	1.042	1.032	1.024	1.016	12	1.013	1.001	0.991
8		1.137	1.115	1.096	1.078	1.062	1.048	1.037	1.028	1.020	14	1.017	1.004	0.994
10		1.153	1.124	1.105	1.086	1.070	1.055	1.043	1.033	1.024	16	1.021	1.008	0.997
12			1.127	1.114	1.095	1.078	1.062	1.049	1.038	1.029	18	1.025	1.011	1.000
14			1.130	1.122	1.103	1.086	1.070	1.055	1.044	1.033	20	1.030	1.014	1.002
16			1.147	1.127	1.111	1.094	1.077	1.062	1.049	1.038	25	1.041	1.024	1.010
18				1.130	1.119	1.101	1.084	1.069	1.056	1.044	30	1.054	1.034	1.019
20				1.134	1.125	1.109	1.092	1.076	1.062	1.049	35	1.068	1.045	1.028
25					1.133	1.125	1.109	1.093	1.078	1.064	40	1.082	1.058	1.038
30						1.133	1.124	1.109	1.094	1.080	45	1.096	1.071	1.049
35							1.132	1.124	1.109	1.095	50	1.109	1.084	1.061
40							1.130	1.130	1.127	1.109	55	1.119	1.097	1.073
45								1.129	1.129	1.121	60	1.124	1.108	1.085
50									1.129	1.127	70	1.126	1.122	1.106
55										1.128	80		1.125	1.119
											90			1.124

number of accelerator scale divisions is made. The meter reading is now 9.00 nC. For a plane-parallel chamber of a plate separation of 2 mm and 200 V the recombination correction factor can be determined for $\bar{D}_{air} = 0.65$ mGy per pulse using Fig. 14:

$$M_{u,pp} = 9.00 \times 1.008 = 9.07 \text{ nC}$$

For the cylindrical chamber, $p_{u,cyl}$ has to be determined. Table 11 gives values to be used. The measurements were made at a depth corresponding to 3 cm water. It is accurate enough for this purpose to assume that the mean energy decreases by 2 MeV per cm water. The mean energy at the effective point of measurement, $\bar{E}_z$, is therefore approximately $20-3\times2 = 14$ MeV. A value for $p_{u,cyl}$ of 0.989 is obtained from Table 11 by interpolation.

The absorbed dose to air calibration factor of the plane-parallel chamber can now be computed using eq. (12):

$$N_{D,pp} = \frac{20.3\times97.7\times0.989}{9.07\times1.000} = 216 \text{ mGy nC}^{-1}$$

The plane-parallel ionization chamber is calibrated at one of the national standards laboratories. In this case the standards laboratory will give the air kerma calibration factor, $N_{K,pp}$, of the chamber. Assuming that the chamber is of the type shown in Fig. 10, $N_{K,pp}$ will be equal to 217.7 Gy nC^{-1} and $N_{D,pp} = 217.7\times(1-0.004)\times0.996 = 216$ mGy nC^{-1} according to eq. (13).

Determination of the absorbed dose at the reference point in water

The mean energy of the electrons at the phantom surface is obtained from a determination of R_{50} in PMMA, using eq. (14) to convert to $R_{50,w}$ and then eq. (3) to yield $\bar{E}_0$ (cf. NACP 1980). A value for $\bar{E}_0$ of 9 MeV is obtained.

The absorbed dose at the dose maximum in water is obtained from measurements at the dose maximum in the perspex phantom. The meter reading, $M_{u,m}$, at the dose maximum in PMMA at the depth 1.5 cm is corrected for temperature, pressure and recombination; after these corrections 0.0435 nC is obtained per accelerator monitor unit. The equivalent depth in water, $R_{100,\mathrm{w}}$, obtained from eq. (14), is 1.7 cm. The two parameters $\bar{E}_0$ and $R_{100,\mathrm{w}}$ are used to determine the appropriate value of $(s_{\mathrm{w,air}})_{\mathrm{u}}$ from Table 12. The value of 1.052 is obtained by interpolation. The absorbed dose at the depth of the dose maximum in water can now be calculated from eqs (15) and (16):

$$\left.\begin{array}{ll} D_{\mathrm{w,u}} & = N_{D,\mathrm{pp}} M_{\mathrm{u,m}} h_{\mathrm{m}} (s_{\mathrm{w,air}})_{\mathrm{u}} \\ N_{D,\mathrm{pp}} & = 216.0\ \mathrm{mGy\ nC^{-1}} \\ M_{\mathrm{u,m}} & = 0.0435\ \mathrm{nC\ per\ acc.\ monitor\ unit} \\ h_{\mathrm{m}} & = 1.000\ \mathrm{(PMMA)} \\ (s_{\mathrm{w,air}})_{\mathrm{u}} & = 1.052 \end{array}\right\} D_{\mathrm{w,u}}$$

= 9.88 mGy per accelerator monitor unit

Appendix B—List of symbols

$D_{\mathrm{w,u}}$ = absorbed dose at the reference point in water at the user's radiation quality

$\bar{D}_{\mathrm{air,u}}$ = mean absorbed dose to air in the cavity of the ionization chamber in water at the user's radiation quality

$\bar{D}_{\mathrm{air,c}}$ = as above but at the calibration quality free in air

$\bar{E}_0$ = mean energy at the phantom surface in an electron beam

$E_{\mathrm{m,a}}$ = maximum energy in the initial accelerator beam

$E_{\mathrm{p,a}}$ = most probable energy in the initial accelerator beam

$E_{\mathrm{p,0}}$ = most probable energy at the phantom surface in an electron beam

g = fraction of the energy of secondary charged particles lost to bremsstrahlung in air

h_{m} = ratio of the signal measured in an electron beam at the ionization maximum on the central axis in a water phantom to that measured for the same irradiation conditions at the ionization maximum in the phantom material

J_{100}/J_{200} = ratio of ionization measured on the central axis in a photon beam at 100 mm depth in a water phantom to that at 200 mm for identical irradiation at a field size of 10 cm × 10 cm and an SSD of 1 metre

b_{m} = ratio of practical range in water to that in a different material for identical irradiations (also used for other ranges for $\bar{E}_0 \leqslant 15$ MeV; written as k in NACP 1980)

k_{att} = corrects for attenuation and scattering in the ionization chamber (+ build-up cap) at the calibration in the ^{60}Co gamma beam

k_{m} = corrects for lack of air-equivalence of the ionization chamber (+ build-up cap) material at the calibration in the ^{60}Co gamma beam

k_{pp} = analogous to the product $k_{\mathrm{att}} k_{\mathrm{m}}$ but for the plane-parallel chamber

$K_{\mathrm{air,c}}$ = kerma in air at the position of the centre of the ionization chamber in the absence of the chamber at the calibration in the ^{60}Co gamma beam

M_{c} = meter reading at calibration (cylindrical chamber) corrected for temperature, pressure etc.

$M_{\mathrm{u,w}}$ = meter reading in water at the user's quality corrected for temperature, pressure, recombination etc. (written as $\mathrm{M_u}$ in NACP 1980)

$M_{\mathrm{u,m}}$ = as above but in a plastic phantom

$N_{D,\mathrm{cyl}}$ = absorbed dose to air ionization chamber factor for a cylindrical chamber (written as N_D in NACP 1980)

$N_{D,\mathrm{pp}}$ = as above but for a plane-parallel chamber

$N_{K,\mathrm{cyl}}$ = air kerma calibration factor for a cylindrical chamber (written as N_K in NACP 1980)

$N_{K,\mathrm{pp}}$ = as above but for a plane-parallel chamber

N_X = exposure calibration factor for a cylindrical chamber

$p_{\mathrm{u,cyl}}$ = perturbation factor for a cylindrical chamber in an electron beam (written as p_{u} in NACP 1980)

$p_{u,x}$ = total perturbation factor for a cylindrical chamber with wall material x in a photon beam

$p_{u,pp}$ = perturbation for a plane-parallel chamber in an electron beam

$R_{p,x}$ = practical range in phantom material x

$R_{y,x}$ = depth at which dose is y per cent in phantom material x

$(s_{w,air})_u$ = water-to-air mass stopping power ratio at the user's radiation quality

$\bar{W}/e$ = mean energy expended in air per ion pair formed

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