

**The Calibration and Use of Plane-Parallel Ionization  
Chambers for Dosimetry of Electron Beams**



AAPM REPORT NO. 48

# The Calibration and Use of Plane-Parallel Ionization Chambers for Dosimetry of Electron Beams

REPORT OF AAPM RADIATION  
THERAPY COMMITTEE TASK GROUP 39

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# The calibration and use of plane-parallel ionization chambers for dosimetry of electron beams: An extension of the 1983 AAPM protocol report of AAPM Radiation Therapy Committee Task Group No. 39

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This report is an extension of the 1983 AAPM protocol, popularly known as the TG-21 Protocol. It deals with the calibration of plane-parallel ionization chambers and their use in calibrating therapy electron beams. A hierarchy of methods is presented. The first is to calibrate the plane-parallel chamber in a high energy electron beam against a cylindrical chamber which has an  $N_{\text{gas}}^{\text{cyl}}$  value that has been obtained from a NIST traceable  $^{60}\text{Co}$  beam calibration. The second method, which is recommended for implementation by the ADCLs is an in-air calibration against a NIST-traceable calibrated cylindrical chamber in a Cobalt-60 beam to obtain a plane-parallel-chamber calibration factor in terms of exposure or air kerma. The third method places the two chambers in a phantom in a Cobalt-60 beam, and leads to an  $N_{\text{gas}}^{\text{pp}}$  value for the plane-parallel chamber. This report also gives  $N_{\text{gas}}^{\text{pp}}/(N_{\text{x-ion}})^{\text{pp}}$  and  $N_{\text{gas}}^{\text{pp}}/(N_{\text{k-ion}})^{\text{pp}}$  values for five commonly used commercially available plane-parallel chambers: the Capintec PS-033, the Exradin P-11, the Holt, the NACP and the PTW-Markus. The calculation of these  $N_{\text{gas}}$  ratios introduces a  $K_{\text{comp}}$  factor which is also calculated for the five parallel plate chambers. The use of the plane-parallel chambers follows the 1983 AAPM protocol for absorbed dose calibrations of electrons, except that new energy-dependent  $P_{\text{repl}}$  values are given for the Capintec PS-033 and PTW-Markus chambers consistent with the consensus of reports in the literature. For all the chambers, however,  $P_{\text{repl}}$  is unity for 20 MeV electrons. This report does not address the issue of the use of plane-parallel chambers in calibrating photon beams.

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	<b>I. INTRODUCTION</b>	
	In 1983, the AAPM published a protocol for the determination of absorbed dose from high-energy photon and electron beams. <sup>1</sup> This was the result of the activities of Task Group 21 of the AAPM Radiation Therapy Committee and the protocol has become popularly known as the "TG-21 Protocol." It will be referred to here as the 1983 AAPM protocol. When that protocol was introduced, it addressed several problems that existed with prior protocols. As a prerequisite for its use,	

a  $^{60}\text{Co}$  calibration factor for the user's ionization chamber was required, because as the protocol stated, "Although the  $^{60}\text{Co}$  factor is not a major component of the Protocol, it is given a position of prominence in the flow diagram so as to assure the reader that this national reference standard, which in no small part is responsible for the high level of uniformity in radiation therapy, continues to play an essential but less explicit role." It also stated that "the Protocol requires an ionization chamber having a calibration factor for  $^{60}\text{Co}$  gamma rays directly traceable to NBS (National Bureau of Standards, now known as the National Institute of Standards and Technology, NIST.). The use of a national standard to characterize the response of an ionization chamber assures both accurate and consistent therapy machine calibrations." The phrase "directly traceable" was further defined to mean that the instrument either had been calibrated at NBS or had been calibrated at a AAPM Accredited Dosimetry Calibration Laboratory (ADCL) against a secondary standard that had itself been calibrated at NBS.

The 1983 AAPM protocol recognized that cylindrical ionization chambers are widely used, and that procedures for their in-air exposure calibration are well established, but the same could not be said for plane-parallel chambers. For these chambers, an additional method was presented based upon an intercomparison in phantom with a calibrated cylindrical chamber in a beam of high energy electrons, by the user, to obtain  $N_{\text{gas}}^{\text{PP}}$ —the dose to the gas in the chamber per electrometer reading, corrected for ionic recombination.

Since the development of the 1983 AAPM protocol, various investigations<sup>2-14</sup> have shown some significant discrepancies and problems in the calibration and use of plane-parallel chambers. In addition, various "in-air" calibration techniques have been employed at the ADCLs, with or without the use of additional backscattering materials, which have resulted in confusion in how the calibration factor should be interpreted when the chamber is used.

Recognizing the need for consistent methods for dealing with these chambers the AAPM Radiation Therapy Committee constituted Task Group 39 to address the following specific charges:

- (i) to make specific recommendations for the calibration of plane-parallel chambers by the Accredited Dosimetry Calibration Laboratories (ADCLs), and
- (ii) to provide guidelines, following the 1983 AAPM protocol, for the determination of absorbed dose from high energy electron beams using the calibrated plane-parallel chambers.

Section III of this report, therefore is addressed primarily to the ADCLs.

Section IV of this report provides the guidelines to the user on how to employ the calibrated plane-parallel chambers to determine absorbed dose under standard conditions, for electron beams.

*The reader is cautioned not to confuse the two sections.* In particular, the conditions and procedures to be followed during the chamber calibration do not apply to the conditions and procedures to be followed when they are used to calibrate electron beams. The task group was not charged with

nor did it address the issue of the use of plane-parallel chambers in calibrating photon beams.

This report presents the final recommendations of Task Group 39 which have been approved by the Radiation Therapy Committee and the AAPM Science Council (pending). These recommendations should now be treated as an extension of the 1983 AAPM protocol.

## II. BACKGROUND

Reich<sup>15</sup> has discussed the problems faced with traceability and which dosimetric quantities should be used. These were summarized by Dutreix and Bridier.<sup>16</sup> Ideally, the same quantity should be used within the calibration chain from primary standards to field instruments. In order to have few correction factors, the quantity used for primary standards should be close to the physical effect on which the standard is based. Hence exposure, which is based upon the ionization of air by x rays, is an ideal quantity for primary standards. Historically, this also served well for field instruments when exposure was the basic quantity in which radiotherapy doses were prescribed and when the photon energy range was within the limits measurable by exposure for x rays. However, since absorbed dose has been recognized as the physical quantity which best correlates with clinical biological effects, the quantity in terms of which a field instrument should be calibrated should be closest to the needed quantity, i.e., absorbed dose to water. Other reasons for using absorbed dose to water are: (i) x-ray energies have far surpassed the few MeV which represents the upper limit for which exposure can be measured accurately, and for which exposure or air kerma calibration factors are available; (ii) electrons are becoming increasingly used, up to (approximately) 20% of all radiotherapy treatments, for which exposure or air kerma cannot be used. Calibration of ionization chambers directly in dose would allow the user to obtain the required numerical value for their beam calibration with as few correction factors as possible. However, in spite of these reasons, the continued use of exposure calibration factors is recommended for the following reasons. Under the present system of the 1983 AAPM protocol, the quantity transmitted by the standardizing laboratories is exposure, through  $N_x$ , or more recently air kerma, through  $N_k$ . This has worked well for cylindrical chambers and the 1983 AAPM protocol allowed for the change in quantities (exposure to absorbed dose) by the introduction of the cavity-gas calibration factor  $N_{\text{gas}}$ . This report is an extension of the 1983 protocol and for the sake of consistency  $N_x$  and  $N_k$  will continue to be used.

However, the calibration of plane-parallel chambers presents a number of special problems which are discussed below. Because of this task group believes that for these chambers calibrated under certain conditions  $N_{\text{gas}}^{\text{PP}}$  should be supplied by standardizing laboratories. Traceability is still maintained, although less apparent, through the determination of  $N_{\text{gas}}$  from  $N_x$  for the standard chamber against which the plane-parallel chambers are compared. In these cases the standardizing laboratories will make the change from exposure to absorbed dose, rather than the user but the process remains essentially the same.

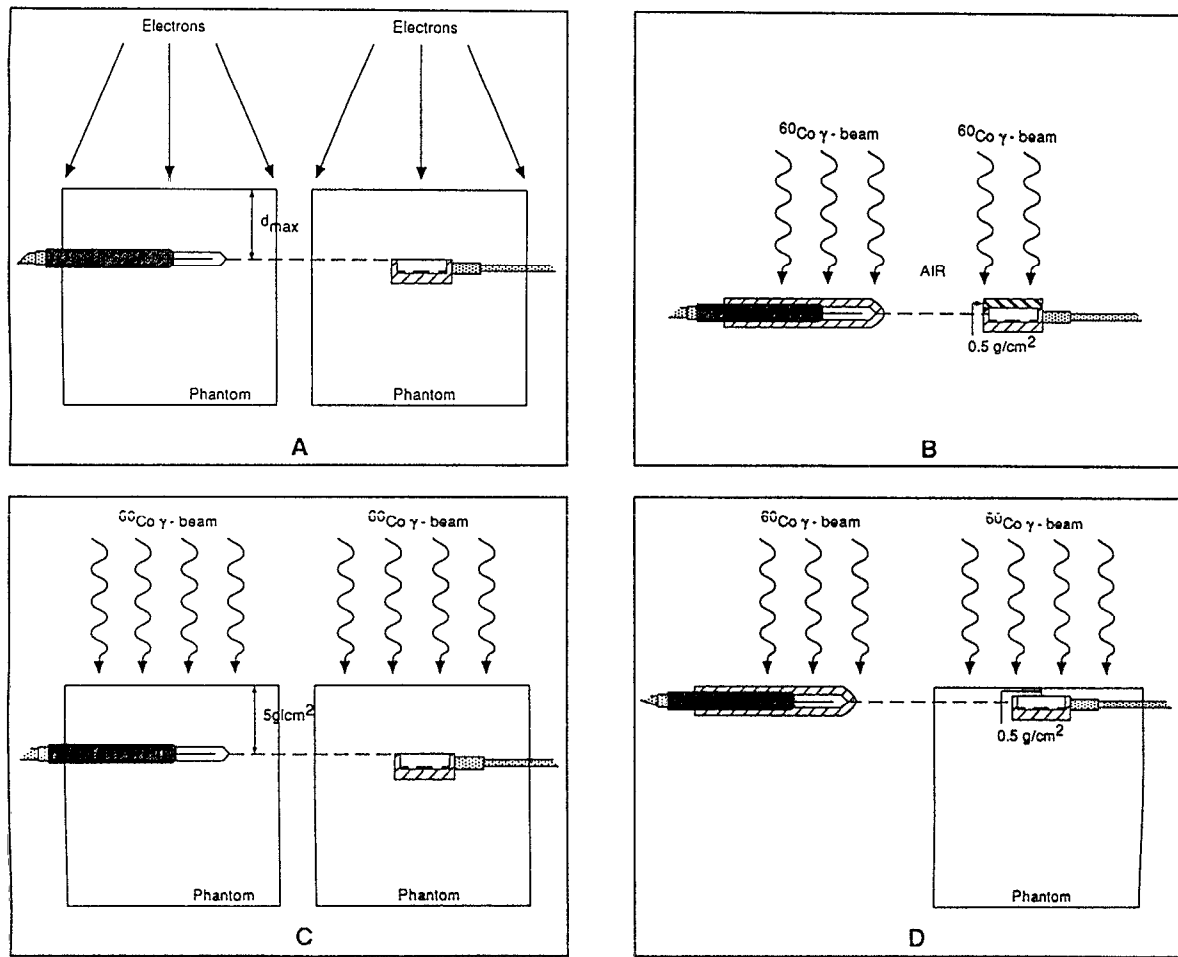


FIG. 1. Schematic illustration of the irradiation geometries used for making calibrations of parallel-plate chambers with cylindrical chambers [Krithivas and Rao (Ref. 6) and Mattson *et al.* (Ref. 9)]: (a) Calibration with 20 MeV electrons. The cylindrical chamber is aligned with the midpoint of its collecting volume located on the beam axis at  $d_{max}$  and its axis of rotation perpendicular to the beam axis and the plane-parallel chamber is with its midpoint of the inner surface of its front wall located on the beam axis at and the chamber walls perpendicular to that axis. (b) "In-air" calibration of a parallel-plate chamber using a Co-60 beam. Point of measurement taken as the chamber center. (c) Calibration "in-phantom at depth," with a Co-60 beam, both chambers are placed in phantoms at depth of  $5 \text{ g/cm}^2$ . Point of measurement taken as the center of the cylindrical chamber and the inner surface of the proximal electrode of the plane-parallel chamber. (d) Calibration "in-phantom at dose maximum," with a Co-60 beam. The parallel-plate chamber was placed in the phantom with full backscatter at  $d_{max}$  (determined by measurement). Point of measurement taken as the chamber center. In all cases, the cylindrical chamber is shown on the left and the plane-parallel chamber on the right.

Several methods for the calibration of plane-parallel chambers have been reported in the literature.<sup>1,2,6,7,9,10,12,17-20</sup> These are shown in Fig. 1 and can be described as follows.

- (a) Calibration with high energy electrons in phantom. The location of the point of measurement is taken as the center of the cylindrical chamber and the inner surface (of the wall that is proximal to the source) of the plane-parallel chamber, respectively. The point for each chamber is placed at  $d_{max}$  for the ionization curve as determined by measurement for the electron beam being used, and the field size is measured at the phantom surface [Fig. 1(a)]. See Sec. III A.
- (b) "In-air" calibration of a plane-parallel chamber using a  $^{60}\text{Co}$  beam with a fixed source-to-detector distance (SDD) and field size (FS), measured at the SDD, with the point of measurement being taken as the chamber center, and with buildup cap required for both chambers [Fig. 1(b)]. See Sec. III B.
- (c) Calibration "in phantom at depth," with a  $^{60}\text{Co}$  beam, both chambers being placed in phantoms at depth  $d = 5 \text{ g/cm}^2$ . The point of measurement is taken as the center of the cylindrical chamber and at the inner surface (of the wall that is proximal to the source) of the plane-parallel chamber [Fig. 1(c)]. See Sec. III C.
- (d) Calibration "in phantom at dose maximum," with a  $^{60}\text{Co}$  beam. The plane-parallel chamber is placed in the phantom at  $d_{max}$  with full backscatter (determined by measurement). The point of measurement is taken as the chamber center. The SDD and field size are the same as for the "in-air" method. The comparison is made with a cylindrical chamber irradiated in-air [Fig. 1(d)].
- (e) Although method D has been discussed by several investigators<sup>10,17,21</sup> it is essentially the same as method B, the two being related by the backscatter factor. There are only three independent methods, therefore,

TABLE I. Recommended values of  $N_{\text{gas}}^{\text{PP}}/(N \times A_{\text{ion}})^{\text{PP}}$  and  $N_{\text{gas}}^{\text{PP}}/(N_K A_{\text{ion}})^{\text{PP}}$  for five commercially available plane-parallel chambers. Factors to be applied in the calibration and use of plane-parallel chambers.

Chamber	Buildup <sup>a</sup> material or phantom material	$A_{\text{wall}}^b$	$K_{\text{comp}}^c$ and $P_{\text{wall}}^{\text{PP}}$	$N_{\text{gas}}^{\text{PP}}/(N_x A_{\text{ion}})^{\text{PP}^d}$ ( $10^{-3}$ Gy/R)	$N_{\text{gas}}^{\text{PP}}/(N_K A_{\text{ion}})^{\text{PP}^e}$
Capintec PS-033	Polysty	1.0022	0.960	8.84	1.005
Exradin P-11	Polysty	1.0016	1.000	8.48	0.964
Holt	Polysty	1.0097	1.000	8.55	0.972
NACP	Graphite	1.0016	1.027	8.45	0.961
PTW-Markus	Acrylic	1.0030	1.000	8.59	0.977

<sup>a</sup>The buildup material of thickness 0.5 g/cm<sup>2</sup> is added to the front face of the chamber, except for the Holt in which the buildup material is inherent in the design.

<sup>b</sup>From Monte Carlo calculations from Rogers (Ref. 12).

<sup>c</sup>From Rogers (Ref. 12) based on Monte Carlo calculations and on available experimental data. These values apply only for the buildup cap or phantom materials in column 2. They have an uncertainty of  $\pm 1\%$  ( $1\sigma$ ).

<sup>d</sup>From Eq. (2) for  $N_x$  in R/unit meter reading (Sec. III B).

<sup>e</sup>From Eqs. (2) and (3) for  $N_K$  in Gy/unit meter reading (Sec. III B).

A, B, and C and these are described in this report, method D is not recommended. Method A employs high-energy electrons, method B makes use of a <sup>60</sup>Co gamma-ray beam with the chambers located at a point in-air, and method C also employs a <sup>60</sup>Co beam but with the chambers placed at depth in a phantom.

- (f) Method C has been reported in the literature<sup>18,21</sup> and has many attractive features about it, not the least being that the chamber position is uniquely determined in a solid phantom making the alignment with the beam precise. However, analysis and discussion of the method by Mattson *et al.*<sup>10</sup> and Rogers<sup>11</sup> has shown that there is substantial uncertainty in the <sup>60</sup>Co value of  $P_{\text{wall}}^{\text{PP}}$ , the correction factor for the chamber material being different from that of the phantom, with values varying from unity by as much as 5% depending upon the chamber, even for nominally matched wall and phantom material. It might be possible to reduce the uncertainty and better determine  $P_{\text{wall}}^{\text{PP}}$  values by comparison of this method with the method employing high energy electrons. However when this is done the in-phantom method using a <sup>60</sup>Co beam relies upon data obtained from the electron beam method and is therefore not independent. The same argument can be made for method B with regard to the effect of the buildup cap and wall material being different which could also be determined experimentally by comparison with the electron beam method. In this report, therefore, we have relied upon Monte Carlo calculations to help resolve these problems.<sup>11,12</sup>
- (g) This report will follow very closely the 1983 AAPM protocol<sup>1</sup> and in basic philosophy is similar to that protocol. The ADCLs maintain radiation standards for exposure  $X$  and for air kerma  $K_{\text{air}}$ , for Cobalt 60, so they provide exposure calibration factors  $N_x$  (or more recently air kerma calibration factors  $N_K$ ). Following the suggestion in the 1983 AAPM protocol, the ADCLs have also been providing the factor  $N_{\text{gas}}^{\text{PP}}/(N_x A_{\text{ion}})^{\text{PP}}$  with which the customer can calculate  $N_{\text{gas}}^{\text{PP}}$  to be used in the 1983 AAPM protocol.

- (h) Method B (<sup>60</sup>Co in-air) continues present procedures at the ADCLs where,  $N_x^{\text{PP}}$ , and air kerma,  $N_K^{\text{PP}}$ , calibration factors will also be assigned along with appropriate  $(N_{\text{gas}}^{\text{PP}}/N_x A_{\text{ion}})^{\text{PP}}$  and  $(N_{\text{gas}}^{\text{PP}}/N_K A_{\text{ion}})^{\text{PP}}$  values provided in Table I of the report for the five common plane-parallel chambers. For method A (electron beam) and C (<sup>60</sup>Co in-phantom) the chamber calibration determines  $N_{\text{gas}}^{\text{PP}}$  directly.

### III. METHODS FOR DETERMINING THE CAVITY-GAS CALIBRATION FACTOR FOR A PLANE-PARALLEL IONIZATION CHAMBER

The three methods which are described in the following sections are valid methods for determining the value of the cavity-gas calibration factor  $N_{\text{gas}}^{\text{PP}}$  for a plane-parallel ionization chamber, through radiation intercomparison with a NET-traceable calibrated cylindrical chamber.

Method A, which employs a beam of high-energy electrons for the intercomparison, is the most direct method for calibrating plane-parallel chambers to be used for electron dosimetry, and is the method specifically referred to by the 1983 AAPM protocol<sup>1</sup> for these chambers. This report also recommends method A as the method of choice where such an electron beam is available. At present, however, there are no primary radiation standards for absorbed dose available for high energy electrons. In addition, the logistics of a secondary standards laboratory (ADCL) providing such calibrations may be prohibitively expensive. Therefore, some of the ADCLs may not offer such a calibration. Thus if the user wants it, the procedure most likely will be carried out at a local accelerator, not at a standardization laboratory. It was this significant disadvantage that prompted the present task group to also recommend calibration procedures B and C that would be within all present ADCL capabilities. Method A, therefore, is presented first, not only to be consistent with the 1983 AAPM protocol, but because it represents the most direct method of obtaining  $N_{\text{gas}}^{\text{PP}}$  and may be used to obtain the parameters needed for the other methods as discussed above. It has the disadvantage of requiring an additional us-

TABLE II.  $P_{\text{repl}}^{\text{PP}}$  factors for various chambers. For the Holt and NACP chambers  $P_{\text{repl}}^{\text{PP}}$  is taken as unity for all energies. For the Markus chamber  $P_{\text{repl}}^{\text{PP}}$  is calculated from Eq. (7) and for the Capintec chamber the values are the average of the two data sets in the literature normalized to unity at 20 MeV. When the average electron energy at depth Z is from 2.5 to 20 MeV.

$\bar{E}_z$ (MeV)	Holt, NACP, Exradin		Markus	Capintec
2.5	1.000		0.985	0.956
3	1.000		0.988	0.961
4	1.000		0.992	0.970
5	1.000		0.994	0.977
6	1.000		0.996	0.982
7	1.000		0.997	0.986
8	1.000		0.998	0.989
10	1.000		0.999	0.994
12	1.000		1.000	0.996
15	1.000		1.000	0.998
20	1.000		1.000	1.000

er's calibration procedure in the traceability chain. However, if  $N_{\text{gas}}^{\text{PP}}$  is required for plane-parallel chambers not included in this report, only method A is available until the parameters needed for the other methods are known to the required accuracy.

Although there are several plane-parallel ionization chambers available commercially which may be used for electron beam dosimetry, data for only five chambers are presented in this report. They are listed in Table II and are the Capintec PS-033, the Exradin P-11, the Holt, the NACP, and the PTW-Markus. Almost all the data for plane-parallel chambers in the literature refer to these chambers and they are the ones most frequently seen by the ADCLs. Descriptions and characteristics of these chambers have been published in the literature.<sup>11,22</sup> Under normal conditions all these chambers are vented to atmosphere. All readings should therefore be corrected to our density at 22°C, 760 mm Hg (101.31 kPa). All such chambers should be checked at regular intervals, that they are open to atmosphere.

Plane-parallel chambers can have a sizeable polarity effect (difference between the charges collected when positive vs negative voltage is applied). Typical polarity-effect data have been given by Humphries and Slowey,<sup>22</sup> Kubo *et al.*,<sup>7</sup> and Mattson *et al.*;<sup>10</sup> however, it is important to realize that some chambers may not be typical and values differing by greater than 3% have been noted for a given chamber type. Moreover, even larger polarity differences may occur in thin-windowed chambers without overlying dose-buildup material. However most of the chambers listed in this protocol show a polarity effect of less than 2% and it is recommended that chamber exhibiting a value larger than this not be used. All readings for parallel-plate chambers should therefore be taken with both polarities and averaged.

### A. The electron-beam method

It will be useful here to begin by quoting verbatim from the 1983 AAPM protocol, Sec. VII B:

" $N_{\text{gas}}$  for a plane-parallel chamber may be determined as follows. Using the highest electron-beam energy available and the cylindrical chamber for which  $N_{\text{gas}}$  is known, deter-

mine the response per monitor unit at  $d_{\text{max}}$ . Next, place the plane-parallel chamber into the same dosimetry phantom taking care to position the inner surface of its proximal electrode at the depth of the central axis of the cylindrical chamber, and determine its response per monitor unit. The cavity-gas calibration factor for the plane-parallel chamber is given by

$$N_{\text{gas}}^{\text{PP}} = (MN_{\text{gas}}P_{\text{ion}}P_{\text{repl}})^{\text{cyl}} / (MP_{\text{ion}})^{\text{PP}}, \quad (1)$$

where the terms in the numerator apply to the cylindrical chamber, and those in the denominator apply to the plane-parallel chamber."

$M$  is the electrometer reading (C or scale division),  $N_{\text{gas}}$  is the dose to the gas in the chamber per electrometer reading (Gy/C or Gy/scale division),  $P_{\text{ion}}$  is the factor that corrects for ionization recombination losses, and  $P_{\text{repl}}$  is the replacement correction factor.

Several points need emphasis and/or clarification:

- (1)  $M$  is the measured average ionization for positive and negative polarities, in Coulombs or scale division, corrected to air density at 22°C, 760 mm Hg, but *not* corrected for relative humidity, assuming it to be typical of laboratory conditions (50% ± 25%).
- (2) The "highest electron-beam energy available" must be high enough to make the  $P_{\text{repl}}$  value for the cylindrical chamber no smaller than 0.98. For a typical Farmer-type cylindrical chamber of inner diameter 6.3 mm, an electron beam is required, with a mean energy of at least 10 MeV at  $d_{\text{max}}$ , the depth of the measurement is required (See Table VIII in the 1983 AAPM protocol<sup>1</sup>). The mean energy at depth is related approximately to the mean incident energy by the formula given in the footnote below Table VIII.
- (3) Section I of the 1983 AAPM protocol defines  $d_{\text{max}}$  as "Depth on the central axis at which an ionization chamber gives the maximum reading, for electron and photon beams (cm or g/cm<sup>2</sup>). That is,  $d_{\text{max}}$  is taken as the depth of maximum ionization.
- (4) The correct alignment of the cylindrical chamber is with the midpoint of its ion-collecting volume located on the beam axis at  $d_{\text{max}}$ , and its axis of rotation perpendicular to the beam axis. This geometry is appropriate because the  $P_{\text{repl}}$  factors in Table VIII of the 1983 AAPM Protocol were derived from Ref. 23, in which that alignment was employed.
- (5) The corresponding correct alignment of the plane-parallel chamber for the intercomparison is with the midpoint of the inner surface of its front wall located on the beam axis at  $d_{\text{max}}$ , and the flat chamber walls perpendicular to that axis. In principle  $d_{\text{max}}$  for the two chambers may differ, but in high-energy electron beams the depth-dose curve has a broad maximum and hence this is not critical. For clarity,  $d_{\text{max}}$  as defined by the cylindrical chamber is used for both.
- (6) In Section IV A of the 1983 AAPM protocol it is recommended that the equilibrium buildup cap used in the <sup>60</sup>Co gamma-ray calibration of the cylindrical chamber

(e.g., Farmer type) be removed for all electron-beam measurements, and that  $P_{\text{wall}}$  be taken as unity [hence it does not appear in Eq. (1)].

- (7) Electron-beam diameters should be large enough to provide complete in-scattering to the beam axis. Conservatively this requires a beam diameter of twice the range  $R_p$  of the electrons in the phantom medium. Thus a beam diameter (cm) numerically equal to the incident electron energy (MeV) is ample (assuming unit density).
- (8) The quantity  $N_{\text{gas}}^{\text{cyl}}$  in Eq. (1) is derived from the NIST calibration value of  $N_x^{\text{cyl}}$  or  $N_K^{\text{cyl}}$  for the chamber. Equation (6) in Ref. 1 relates  $N_{\text{gas}}^{\text{cyl}}$  to  $N_x^{\text{cyl}}$  based on the conditions present during the NIST calibration of the chamber in a  $^{60}\text{Co}$  gamma-ray beam:

$$N_{\text{gas}}^{\text{cyl}} = \frac{N_x^{\text{cyl}} k (W/e)_{\text{gas}} A_{\text{ion}} A_{\text{wall}} \beta_{\text{wall}}}{(\bar{L}/\rho)_{\text{gas}}^{\text{wall}} (\bar{\mu}_{\text{en}}/\rho)_{\text{wall}}^{\text{air}} K_{\text{comp}}^{\text{cyl}}}, \quad (2a)$$

where  $N_x^{\text{cyl}}$  is stated in R/C, R/scale division,  $\text{Ckg}^{-1}/\text{C}$  or  $\text{Ckg}^{-1}/\text{scale division}$   $k = 2.58 \times 10^{-4} \text{Ckg}^{-1} \text{R}^{-1}$  or unity if exposure is stated in  $\text{Ckg}^{-1}$ ,  $(W/e)_{\text{gas}} = 33.7 \text{ J/C}$ . Although, the effect of humidity upon the equations and the value of  $(W/e)$  has been discussed in the literature.<sup>3,15</sup> The present values are used to be consistent with the 1983 AAPM protocol and the  $N_{\text{gas}}/N_K A_{\text{ion}}$  values of Gastorf *et al.*<sup>24</sup>

$A_{\text{ion}}$  is the ion-collection efficiency, at the time of calibration.

$A_{\text{wall}}$  is the correction factor for attenuation and scattering of gamma rays in the chamber wall and buildup cap.

$\beta_{\text{wall}}$  is the quotient of absorbed dose by the collision kerma in the chamber wall.  $\beta_{\text{wall}} = 1.005$  for  $^{60}\text{Co}$  gamma rays.

$(\bar{L}/\rho)_{\text{gas}}^{\text{wall}}$  is the mean restricted mass stopping power ratio for the chamber wall material relative to the gas (ambient air) inside, obtained from Table I of Ref. 1,

$(\bar{\mu}_{\text{en}}/\rho)_{\text{wall}}^{\text{air}}$  is the mean mass energy absorption coefficient ratio for dry air relative to the chamber wall material, obtained from Table I of Ref. 1.

$K_{\text{comp}}$  following Rogers<sup>25,26</sup> corrects for the composite nature of the chamber and build-up cap. For a cylindrical chamber and buildup cap it is given by

$$K_{\text{comp}}^{\text{cyl}} = \frac{\alpha (\bar{L}/\rho)_{\text{gas}}^{\text{wall}} (\bar{\mu}_{\text{en}}/\rho)_{\text{wall}}^{\text{air}} + (1 - \alpha) (\bar{L}/\rho)_{\text{gas}}^{\text{cap}} (\bar{\mu}_{\text{en}}/\rho)_{\text{cap}}^{\text{air}}}{(\bar{L}/\rho)_{\text{gas}}^{\text{wall}} (\bar{\mu}_{\text{en}}/\rho)_{\text{wall}}^{\text{air}}}, \quad (2b)$$

where  $\alpha$  is the fraction of ionization due to electrons arising from photon interactions in the chamber wall and  $(1 - \alpha)$  is the fraction of ionization due to electrons arising from photon interactions in the buildup material.

Combining Eqs. (2a) and (2b) yields Eq. (6) of Ref. 1. If  $K_{\text{comp}}^{\text{cyl}} = 1$  then Eq. (2a) reduces to Eq. (5) of Ref. 1.

In this report the exact version of the 1983 AAPM Protocol's equation for  $N_{\text{gas}}$  is used despite several known inconsistencies.<sup>25-28</sup> In particular the protocol used  $(W/e)_{\text{gas}} A_{\text{wall}} \mathbf{b}_{\text{wall}}$  where it should have been  $(W/e)_{\text{air}} A_{\text{wall}}$  ( $\beta_{\text{wall}}$  is implicit in the method of determining  $A_{\text{wall}}$ ). However  $(W/e)_{\text{air}} = 33.97 \text{ J/C}$  and  $(W/e)_{\text{gas}} \mathbf{b}_{\text{wall}} = 33.87 \text{ J/C}$ . Since the two errors cancel to a large degree and since it is

desirable to remain consistent with the protocol we recommend using the original equations despite the known problems.

(9) If the NIST calibration of the cylindrical chamber is stated as an air-kerma calibration factor,  $N_K$  in Gy/C, the value of  $N_x$  in R/C for use in Eq. (2) can be obtained from

$$N_x = N_K (1 - g) / k (W/e)_{\text{air}}, \quad (3)$$

where  $g$  (the average fraction of secondary electron kinetic energy that is spent in bremsstrahlung production). NIST takes  $g$  as 0.0032 and  $(W/e)_{\text{air}}$  for dry air as 33.97 J/C for  $^{60}\text{Co}$  gamma rays. Thus for these values  $N_x = 113.7 N_K$ .

(10) Recommended values of  $N_{\text{gas}}/N_K A_{\text{ion}}$  for the cylindrical chambers commonly used can be found in Gastorf *et al.*<sup>24</sup>  $N_{\text{gas}}/N_K A_{\text{ion}}$  values can be determined using Eq. (3).

## B. The $^{60}\text{Co}$ in-air method

In this method the intercomparison between the plane-parallel chamber and the NIST calibrated spherical or cylindrical chamber is performed in a  $^{60}\text{Co}$  gamma-ray beam in air. An exposure or air-kerma calibration factor  $N_x^{\text{PP}}$  or  $N_K^{\text{PP}}$  will be obtained for the plane-parallel chamber by direct comparison with the spherical or cylindrical chamber and  $N_{\text{gas}}^{\text{PP}}$  are obtained from given  $N_{\text{gas}}^{\text{PP}}/(N_x A_{\text{ion}})^{\text{PP}}$  values.

The following procedures should be followed.

- (1) The plane-parallel chamber should be submitted to the ADCL for calibration with the necessary dose-buildup material in place, unless the proximal wall is already thick enough, as is the case for the Holt chamber. The added buildup material should have the same outer diameter as the chamber, and be of the material specified in Table I, its thickness should be  $0.5 \text{ g/cm}^2$  to ensure charged-particle equilibrium and to exclude electron contamination that may be present in the  $^{60}\text{Co}$  beam and to match the calculated  $A_{\text{wall}}$  values given in Table I.
- (2) The  $^{60}\text{Co}$  beam should be  $10 \times 10 \text{ cm}^2$  at the chamber measurement location, at a distance of at least 80 cm from the source.
- (3) The correct alignment of the plane-parallel chamber for the intercomparison is with the *midpoint* of its ion-collecting volume located on the beam axis at the measurement location, and its flat chamber walls perpendicular to that axis. This is the point of measurement for in-air calibrations only and is required by the ion-chamber theory used to extract  $N_{\text{gas}}$ . Similarly, the user provided buildup cap material must be in place for the in-air calibration only.
- (4) The corresponding correct alignment of the ADCLs spherical or cylindrical chamber used in the intercomparison is with the midpoint of its ion-collecting volume located on the beam axis at the measurement location, and its axis of rotation perpendicular to the beam axis. The buildup cap used in its NIST-traceable calibration must be in place.
- (5) No phantom material is to be placed in the beam with either chamber, except what is already an integral part of

the chamber's construction and the buildup material or buildup cap. The applicability of the factors in Table I depends on this.

- (6) Under these conditions, the exposure calibration factor for the plane-parallel chamber is given by

$$N_x^{pp} = N_x^{cyl} M^{cyl} / M^{pp}, \quad (4)$$

where  $M^{cyl}$  and  $M^{pp}$  are, respectively, the meter readings of the cylindrical (or spherical) and plane-parallel chambers under the above conditions, corrected for temperature and pressure as in Sec. III A(1) with  $M^{pp}$  being the average reading for positive and negative polarity. The same equation holds when  $N_x$  is replaced for both chambers by  $N_x$ , the air kerma calibration factor.

(7) The ratios of  $N_{gas}^{pp} / (N_x A_{ion})^{pp}$  and  $N_{gas}^{pp} / (N_k A_{ion})^{pp}$  as tabulated in Table I, were obtained from Eqs. (2a) and (3) with the superscript changed from cyl to pp and  $A_{wall}$  and  $K_{comp}^{pp}$  values recommended by Rogers<sup>11,25</sup> based on Monte Carlo calculations and comparisons to measured data.

(8) If a spherical chamber is used by the ADCL then the subscript cyl should be replaced throughout this method by the subscript sph.

### C. The <sup>60</sup>Co in-phantom method

In this method, the intercomparison between the plane-parallel chamber and the NIST-calibrated cylindrical chamber is performed in a <sup>60</sup>Co gamma-ray beam at a depth of 5 g/cm<sup>2</sup> in a phantom of material selected to match that of the plane-parallel chamber, as described in Ref. 18.  $N_{gas}^{pp}$  is related to the known value of  $N_{gas}^{cyl}$  by

$$(M/A_{ion})^{pp} (N_{gas} P_{wall})^{pp} = (M/A_{ion})^{cyl} (N_{gas} P_{repl} P_{wall})^{cyl}, \quad (5)$$

where  $M^{cyl}$  and  $M^{pp}$  are, respectively, the meter readings of the cylindrical and plane-parallel chambers under the above conditions, corrected for temperature and pressure as in Sec. III A(1), and  $M^{pp}$  is the average of each polarity.

$A_{ion}$  is the ion-collection efficiency, at the time of calibration,  $N_{gas}^{cyl}$  is obtained from the NIST calibration value of  $N_x^{cyl}$  or  $N_k^{cyl}$  as in Sec. III A (8), (9), and (10),  $P_{repl}$  is the correction factor for the replacement of phantom material by the cavity of the ionization chamber [ $P_{repl}$  is taken as unity in the 1983 AAPM protocol for plane-parallel chambers, so it does not appear on the left-hand side of Eq. (5)], and  $P_{wall}$  is the correction factor to account for the chamber material being different from that of the phantom.

$P_{wall}$  for the plane-parallel chamber is difficult to determine. In the ideal case where the plane-parallel chamber is made of only a single material that is identically matched by the phantom medium,  $P_{wall}$  equals unity. However, the construction of plane-parallel chambers usually employs more than one material. Thus the phantom medium should be selected to match whichever material is the most important contributor of the secondary electrons that produce the measured ionization.

If the chamber has a very thin front wall (for which  $a$  is nearly zero), its influence can be ignored because practically all of the electrons then originate in the phantom medium. That medium should be selected to match the principal ma-

terial of which the thicker rear wall is constructed. Since secondary electrons are projected preferentially in the forward hemisphere by <sup>60</sup>Co gamma ray interactions, the electron backscattering ability of the rear wall (a strong function of atomic number) will be the most important influence on the ionization.

If the chamber has a thicker front wall, for which  $a$  is significantly greater than zero, the phantom medium should be made of that same material. However, if the back wall differs appreciably in atomic number, this in-phantom procedure should not be expected to yield a satisfactory result, due to the difference in electron backscattering from the back wall in comparison with the phantom medium."

Because of the difficulties in calculating  $P_{wall}^{pp}$  for existing commercial plane-parallel chambers of nonhomogeneous design, it has been recommended" that the value be determined experimentally by comparison of the <sup>60</sup>Co in-phantom method with the electron-beam method. By determining the value of  $N_{gas}^{pp}$  from Eq. (1), and inserting it in Eq. (5), one can solve for  $P_{wall}^{pp}$ . That value can then be used in subsequent recalibrations of the same chamber by the <sup>60</sup>Co in-phantom method, or for other chambers of the same design.

Recommended values of  $P_{wall}^{pp}$  are given in Table I from Rogers.<sup>12</sup> These are based upon Monte Carlo calculations and consideration of approximately ten published experimental data sets. The recommended  $P_{wall}^{pp}$  values have a systematic uncertainty of  $\pm 1\%$  ( $1\sigma$ ). A mass depth of 5.0 g/cm<sup>2</sup> for the reference plane simplifies positioning so that the proximal surface of the air gap in the plane-parallel chamber can be conveniently and accurately placed at the same depth and at the same distance from the source, as the plane through the center of the cylindrical chamber.

In order to perform such an  $N_{gas}^{pp}$  calibration of a plane-parallel chamber, the chamber must be enclosed (but vented to atmosphere) in a closely fitting phantom slab 4.0 g/cm<sup>2</sup> thick and approximately 25 cm square. The slab medium must be chosen to match the parallel-plate chamber material as closely as possible. Usually the customer desiring the calibration will be expected to submit the plane-parallel chamber to the ADCL in such a phantom slab. The plane of the proximal surface of the chamber's air gap must be located 2.00  $\pm 0.01$  g/cm<sup>2</sup> from the proximal face of the slab, and be clearly defined by scribe marks on the edges of the slab.

For an ADCL to be able to offer in-phantom <sup>60</sup>Co calibrations of parallel-plate chambers, the ADCL must have a corresponding set of phantom slabs that are drilled to fit the secondary standard cylindrical chamber which is to be used in the intercomparison. These in-house phantom slabs must be made of polystyrene, acrylic\*\* or graphite to match the phantom slabs submitted and which must match the materials listed in Table I. The term "acrylic" has been used throughout this report to be consistent with the 1983 AAPM protocol. The generic name is polymethylmethacrylate or PMMA. Lucite and Perspex are trade names of PMMA. A chamber with a graphite wall and graphite buildup cap in place is recommended as the secondary standard." The total mass-thickness of the graphite wall plus cap should equal the maximum range of the Compton electrons, which is 0.57 g/cm<sup>2</sup>.

During the calibration procedure, the plane-parallel chamber in its slab and the cylindrical chamber in its slab are to be "sandwiched" in turn between the same two layers of acrylic or polystyrene, each 3.0 g/cm<sup>2</sup> thick and approximately 25 cm square, as described in Ref. 18. The chamber slabs, one after the other, would be centered in a 10X10 cm<sup>2</sup> <sup>60</sup>Co gamma ray beam, with the reference plane at a suitable distance from the source (e.g., 1 m).

#### IV. DOSIMETRY PROTOCOL WITH PLANE-PARALLEL CHAMBERS

##### A. Dose to the medium

Once  $N_{\text{gas}}^{\text{pp}}$  has been calculated, the determination of absorbed dose for the user's beam will proceed according to TG-21. Since these chambers are designed primarily for use with electron beams, calibration of those beams only will be presented.

When the chamber is placed in a suitable phantom (medium), the dose to the medium will be given by Eq. (9) of Ref. 1, i.e.,

$$D_{\text{med}} = MN_{\text{gas}}^{\text{pp}} (\bar{L}/\rho)_{\text{gas}}^{\text{med}} P_{\text{ion}} P_{\text{repl}}, \quad (6)$$

where  $M$  is the electrometer reading (Coulombs or scale division corrected to 22°C, 760 mm Hg).  $M$  is the average of the readings obtained with positive and negative voltage applied to the chamber.  $(\bar{L}/\rho)_{\text{gas}}^{\text{med}}$  is the ratio of the mean, restricted collision mass stopping power of the phantom material to that of the chamber gas (ambient air) and is given in Tables V, VI, and VII in Ref. 1 (1983 AAPM protocol).  $P_{\text{ion}}$  is the factor that corrects for ionization recombination losses that occur at the time of calibration of the user's electron beam.  $P_{\text{ion}}$  is the inverse of the ionization collection efficiency and has a value equal to or greater than unity. Using the two-voltage technique,  $P_{\text{ion}}$  can be obtained from Fig. 1 in Ref. 3 (TG-25 report) for a voltage ratio of two<sup>1,29</sup> or Table I from Ref. 3 for a voltage ratio of five. Other voltage ratios can be used using the formula in Ref. 29.  $P_{\text{repl}}$  is the replacement correction which is discussed below. Equation (9) of Ref. 1 also includes the factor  $P_{\text{wall}}$ . Although there is some indication in the literature that  $P_{\text{wall}}$  may differ from unity for some chambers,<sup>30</sup>  $P_{\text{wall}}$  is taken as unity for electrons in this protocol to be consistent with the 1983 AAPM protocol and is not included in Eq. (6).

##### B. The replacement correction factor $P_{\text{repl}}$

In the 1983 AAPM protocol the replacement correction factor  $P_{\text{repl}}$  is taken as unity for plane-parallel chambers irrespective of electron-beam energy. However, since 1983 a number of investigators<sup>2-4,7,8,10,13,31-34</sup> have reviewed this parameter with the work of Reft and Kuchnir<sup>8,33</sup> and Wittkamper *et al.*<sup>13</sup> being comprehensive summaries of the data. For electron beams of energies exceeding about 15 MeV,  $P_{\text{repl}}^{\text{pp}}$  should closely approach unity for all plane-parallel chambers, and that is assumed to be true in this report. Some data in the literature are normalized to unity in this energy range,<sup>7</sup> while others are not<sup>20</sup> and show differences from unity. However Rogers<sup>12</sup> has pointed out that such data can be interpreted alternatively as giving  $P_{\text{repl}}$  unity if one as-

signs an appropriate nonunity value to  $P_{\text{wall}}^{\text{pp}}$  in their comparative <sup>60</sup>Co measurements. That alternative has been adopted here.

Two of the commercial chambers (Capintec and Markus) that are dealt with in this report show clear experimental evidence that  $P_{\text{repl}}$  decreases with decreasing electron energy. Most of the published data concerns the Markus chamber. An analysis of this information shows large uncertainties in many reported  $P_{\text{repl}}$  values and differences of several percent for some values at the same energy. The Netherlands Commission on Radiation Dosimetry in their Code of Practice for the Dosimetry of High-Energy Electron Beams<sup>35</sup> considered this situation for the Markus chambers and recommended the following equation for  $P_{\text{repl}}$  (designated  $p_f$  in their protocol)

$$P_{\text{repl}} = 1 - 0.041 e^{-0.4 \bar{E}_z}, \quad (7)$$

Table II lists  $P_{\text{repl}}$  values for the Markus chamber from this equation.

For the Capintec chamber there are only two sets of data.<sup>7,8</sup> These have been used to derive the values listed in Table II.

There are no experimental values below  $\bar{E}_z = 2.5$  MeV so extrapolation of  $P_{\text{repl}}$  below 2.5 MeV for the Markus and Capintec chambers will introduce even greater uncertainties and it is recommended not to use these chambers below this energy.

For the other chambers, for which the guard ring width is at least 3 mm,  $P_{\text{repl}}$  has been found to remain practically constant at unity throughout the energy range covered by Table II.

##### C. Depth of calibration

For electron beams, the calibration depth is restricted to  $d_{max}$ , the depth of maximum ionization in both plastic and water phantoms. Plane-parallel chambers are positioned with the inner surface of the proximal electrode at  $d_{max}$ , and the dose so determined is at this depth.

##### D. Scaling factors and dose transfer, plastic to water

Absorbed dose measured with plane-parallel chambers in plastic phantoms requires corrections to obtain the dose to water. These have been discussed in detail in Ref. 36. When secondary electron equilibrium exists and the energy spectra at the point of interest in both media are the same, then,

$$D_{\text{water}}(d_{\text{water}}) = D_{\text{med}}(d_{\text{med}}) [(\bar{S}/\rho)_{\text{coll,med}}^{\text{water}} / \phi_{\text{med}}^{\text{water}}], \quad (8)$$

where the depth in water  $d_{\text{water}}$  is related to the depth in the medium  $d_{\text{med}}$  by

$$d_{\text{water}} = d_{\text{med}} \alpha \rho_{\text{eff}} = d_{\text{med}} (R_{50}^{\text{water}} / R_{50}^{\text{med}}). \quad (9)$$

Here,  $[(\bar{S}/\rho)_{\text{coll,med}}^{\text{water}}]$  is the ratio of the mean unrestricted mass collision stopping power in water to that in the solid.

$\phi_{\text{med}}^{\text{water}}$  is the fluence factor, i.e., the ratio of electron fluence in water to that in the solid phantom.  $\phi_{\text{med}}^{\text{water}}$  is discussed in detail in Ref. 36 (TG-25).

$R_{50}$  is the depth of the 50% ionization.

$r_{\text{eff}}$  is the effective density of the medium and is discussed in Ref. 36 (TG-25) where recommended values of  $r_{\text{eff}}$  are given.

For many plastics  $(\bar{S}/\rho)_{\text{med}}^{\text{water}}$  is very nearly constant for electrons in the range 0.1–50 MeV. The values of 1.030 for a polystyrene medium and 1.033 for polymethylmethacrylate (PMMA) recommended by the 1983 AAPM protocol<sup>1</sup> should be used. Additional electron mass collision stopping powers for the other media can be found in Refs. 36 and 37. The fluence factors  $\phi_{\text{med}}^{\text{water}}$  calculated by Hogstrom and Almond<sup>38</sup> and recommended by AAPM Radiation Therapy Committee Task Group 25 can be found in Tables VIII(a)–(b) of Ref. 36.

The SSD and collimator field size for electron dosimetry in a plastic phantom should be the same as for a water phantom.<sup>36</sup>

## V. SUMMARY

This protocol deals with the calibration and use of plane-parallel ionization chambers, and provides specific data for five commercial models: the Capintec PS-033, the Exradin P-11, the Holt, the NACP, and the PTW-Markus.

It recommends that the primary means of calibrating such chambers is with high energy electrons at  $d_{\text{max}}$  in a phantom, intercomparing with a cylindrical chamber whose  $N_{\text{gas}}^{\text{cyl}}$  value has been obtained from a NIST-traceable <sup>60</sup>Co beam exposure or air-kerma calibration.  $N_{\text{gas}}^{\text{pp}}$  will be calculated following the 1983 AAPM protocol procedure. The electron beam energy must be high enough to ensure that  $P_{\text{repl}}^{\text{cyl}}$  is no smaller than 0.98 and  $P_{\text{repl}}^{\text{pp}}$  is very close to unity.  $P_{\text{wall}}$  is assumed unity for both chambers. In general this will mean an incident electron beam energy of at least 18 MeV.

Plane-parallel chambers may also be calibrated in air at <sup>60</sup>Co to obtain  $N_x^{\text{pp}}$  or  $N_K^{\text{pp}}$ .  $N_{\text{gas}}^{\text{pp}}/(N_x A_{\text{ion}})^{\text{pp}}$  and  $N_{\text{gas}}^{\text{pp}}/(N_K A_{\text{ion}})^{\text{pp}}$  values are given in Table I for the above five chambers. These values depend on buildup material of a thickness of 0.5 g/cm<sup>2</sup> being added to the front chamber wall and an outer diameter equal to that of the chamber. The buildup material to be used with each chamber is also listed in Table I.

Calibration of plane-parallel chambers at a depth of 5 g/cm<sup>2</sup> in a phantom as described in Ref. 18 using the  $P_{\text{wall}}^{\text{pp}}$  values in Table I is also recommended as an alternative method.

It has been shown that the values of  $K_{\text{comp}}$  and  $P_{\text{wall}}$  recommended here for calibrations in-air or in-phantom in a <sup>60</sup>Co beam are in good agreement with a wide range of experimental data<sup>11</sup> based on  $N_{\text{gas}}$  measurements in electron beams and on in-air or in-phantom measurements. This good agreement implies all three methods for determining  $N_{\text{gas}}$  can be treated as equivalent.

For plane-parallel chambers other than the five considered in this report, the only method available for determining  $N_{\text{gas}}$  is method A (electron in phantoms) until reliable values for  $K_{\text{comp}}$  and  $P_{\text{repl}}$  for the new chamber have been determined.

The described procedure for applying plane-parallel chambers in the calibration of electron beams follows closely the 1983 AAPM protocol.  $P_{\text{wall}}^{\text{pp}}$  is assumed to be unity but  $P_{\text{repl}}^{\text{pp}}$  values for the Capintec and Markus chambers depend

on electron energy, as indicated in Table II. It is likely that the plane-parallel chambers will be used in plastic phantoms for beam calibration purposes, and this protocol follows the AAPM Task Group 25 Report<sup>36</sup> protocol in the method of obtaining absorbed dose to water from absorbed dose to plastic.

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## APPENDIX: SYMBOLS

$\alpha$  is the fraction of ionization due to electrons arising from photon interactions in the chamber wall and  $(1-\alpha)$  is the fraction of ionization due to electrons arising from photon interactions in the surrounding material (buildup or phantom).

$A_{\text{ion}}$  is the ion-collection efficiency, in the <sup>60</sup>Co beam, at time of calibration and is provided by the calibration laboratory.

$A_{\text{wall}}$  is the correction factor for attenuation and scattering of gamma-rays in the chamber wall and buildup cap.

$b_{\text{wall}}$  is the quotient of absorbed dose by collision kerma in the chamber wall (i.e., under conditions of transient charged particle equilibrium). Its value is implicitly included in all tabulated  $A_{\text{wall}}$  values but is retained explicitly here to conform to the 1983 AAPM protocol.

$d_{\text{max}}$  is the depth on the central axis at which an ionization chamber gives the maximum reading for electron or photon beams (cm or g/cm<sup>2</sup>).

$D_{\text{med}}$  is the absorbed dose to the medium at the position of the chamber, with the chamber replaced by medium.

$\bar{E}_z$  is the mean electron energy at depth of measurement (MeV) and is given approximately by  $\bar{E}_z = E_0(1 - Z/R_p)$ , where  $\bar{E}_0$  is the mean incident energy of an electron beam (MeV),  $Z$  is the depth of measurement (cm) and  $R_p$  is the practical range (cm).

$k = 2.58 \times 10^{-4} \text{ C kg}^{-1} \text{ R}^{-1}$  or unity if exposure is stated in  $\text{C kg}^{-1}$ .

$K_{\text{air}}$  is the kerma to air.

$K_{\text{comp}}$  is the correction factor to account for composite wall materials, including the buildup material, in the ioniza-

tion chamber at the time of the chamber calibration with  $^{60}\text{Co}$  gamma rays.

$(\bar{L}/\rho)_{\text{gas}}^{\text{wall}}$  is the mean restricted mass stopping power ratio for the chamber wall relative to the gas (ambient air) inside.

$M$  is the measured ionization in Coulombs, corrected to air density at 22°C, 760 mm Hg, but *not* corrected for relative humidity, assuming it to be typical of laboratory conditions (50% +/- 25%).

$(\bar{\mu}_{\text{en}}/\rho)_{\text{wall}}^{\text{air}}$  is the mean mass energy absorption coefficient ratio for dry air relative to the chamber wall.

$N_{\text{gas}}$  is the cavity-gas calibration factor (Gy/C or Gy/scale division).

$N_x$  is the exposure calibration factor (R/C, R/scale division, Ckg<sup>-1</sup>/C or Ckg<sup>-1</sup>/scale division) for  $^{60}\text{Co}$  radiation.

$N_k$  is the air-kerma calibration factor (Gy/C or Gy/scale division) for  $^{60}\text{Co}$  radiation.

$P_{\text{ion}}$  is the ion recombination correction factor applicable to the calibration of the user's beam.

$P_{\text{repl}}$  is the correction factor for the replacement of phantom material by the cavity of an ionization chamber.

$P_{\text{wall}}$  is the correction factor for the chamber material being different from that of the phantom.

$S_{\text{eff}}$  is effective density.

$\phi_{\text{med}}^{\text{water}}$  is the ratio of the electron fluence at depth  $d_{\text{water}}$  in water to that at depth  $d_{\text{med}}$  in plastic.  $d_{\text{water}} = d_{\text{med}} \times S_{\text{eff}}$

$(\bar{S}/\rho)_{\text{med}}^{\text{water}}$  is the ratio of the average unrestricted mass collision stopping power of water to that of another medium.

$(W/e)_{\text{air}}$  is the mean energy expended per unit charge in dry air = 33.97 J/C.

$x$  is the exposure.

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