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TWO NEW PARALLEL-PLATE IONIZATION CHAMBERS FOR ELECTRON BEAM DOSIMETRY

C. N. DE SOUZA,* L. V. E. CALDAS,† C. H. SIBATA,* A. K. HO* and K. H. SHIN*

*Roswell Park Cancer Institute, Radiation Medicine Department, Elm and Carlton Streets, Buffalo, NY 14263, U.S.A.; and †Instituto de Pesquisas Energéticas e Nucleares/CNEN, Travessa R, 400, Pinheiros, São Paulo, S.P., Brazil 05499

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Abstract—Two parallel-plate ionization chambers were projected, constructed and evauated for use in high energy electron beams. They were constructed using the two plastic materials recommended for clinical dosimetry protocols, i.e. acrylic and polystyrene. Both chambers have cylindrical shape with entrance windows in aluminized Mylar and they are open to the air. The acrylic chamber has a 2 mm air gap and the polystyrene chamber has a 1 mm air gap. Pre- and post-irradiation leakage, repeatability and long term stability were determined for these two ionization chambers. The ionic recombination and polarity effects, besides angular and energy dependencies, were also verified. The results obtained are within values recommended by IEC (1982) [Medical electrical equipment: dosimeters with ioniz chamber as used in radiotherapy. IEC, Geneva (IEC-731-82)] for this kind of ionization chamber. The ionization chambers were calibrated in a 20 MeV electron beam and gamma radiation of cobalt-60. The wall correction factors for the gamma radiation of cobalt-60 were 1.014 and 1.000 for the acrylic and polystyrene chambers, respectively. The ionization chambers do not present the energy dependence for the 6–20 MeV electron beam range. These results are comparable to commercially available ionization chambers.

1. INTRODUCTION

Over the last years, attention has been focused on parallel-plate ionization chambers for electron beam dosimetry (AAPM, 1983, 1991, 1994), especially for low-energy electron beams. Due to the uncertainty on the location of the effective point of measurement and the large replacement correction for cylindrical chambers, when used in phantoms, most dosimetry protocols (AAPM, 1983, 1991, 1994) recommend using parallel-plate ionization chambers in the determination of the absorbed dose for electron beams below 10 MeV.

The response of an ionization chamber is sensitive to the size and the geometry of the material used in its construction. P_{wall} corrects the response of an ionization chamber for the fraction of electrons originating in the chamber wall. According to AAPM (1983), P_{wall} for a parallel-plate ionization chamber can be unity, if the ionization chamber is made predominantly of the same material as that used for the phantom. Recently, Rogers (1992) showed that the ionization chamber response depends strongly on the chamber construction. AAPM (1994) presents P_{wall} for several parallel-plate ionization chambers. A parallel-plate ionization chamber should have an adequate guard width to make the replacement correction minimal. A replacement correction factor, P_{repl}, depends upon the type and energy of the radiation, the gradient of the depth–dose curve at the point of measurement, and the radius of the chamber cavity. According to AAPM (1983), replacement corrections consist of (1) gradient corrections, and (2) electron fluence corrections. For photon beam calibration, a parallel-plate ionization chamber does not require any replacement corrections. For cylindrical ionization chambers, the protocol provides P_{wall} and the electron fluence correction. For parallel-plate ionization chambers having guarded fields and internal heights and diameters of the order of 2 and 20 mm, respectively, the suggested electron fluence correction is unity (Mattsson *et al.*, 1981; AAPM, 1983, 1994).

In Brazil, there is interest in studying and developing such ionization chambers, because there are difficulties importing and servicing them. Different models of ionization chambers were designed and constructed: thimble-type ionization chambers (Campos, 1982; Rodrigues *et al.*, 1986); an extrapolation ionization chamber (Silva, 1985); graphite transmission ionization chambers (Austerlitz *et al.*, 1987); and parallel-plate ionization chambers for low-energy X-ray beams (Albuquerque and Caldas, 1989). At the Calibration Laboratory of São Paulo/CNEN, São Paulo, Brazil, two new parallel-plate ionization chambers were designed and constructed. Tests were performed at Roswell Park Cancer Institute, Buffalo, New York. Besides the metrological performance requirements (IEC, 1982), the simplicity of construction and low cost were also considered.

Table 1. Physical characteristics of the parallel-plate ionization chambers

Characteristic	Chamber PMMA	Chamber Polystyrene
Material	polymethylmethacrylate	polystyrene
Nominal collecting volume	0.056 cm^3	0.078 cm^3
Electrode separation	2.0 mm	1.0 mm
Window material	aluminized Mylar	aluminized Mylar
Window thickness	0.2 $mg\,cm^{-2}$	0.2 $mg\,cm^{-2}$
Collecting electrode material	graphite coating	graphite coating
Collector diameter	6 mm	10 mm
Guard electrode material	graphite coating	graphite coating
Guard electrode width	7 mm	4 mm

2. MATERIALS AND METHODS

The ionization chambers were constructed using, predominantly plastic materials recommended by AAPM protocol (AAPM, 1983), polymethylmethacrylate (PMMA) and polystyrene. The PMMA parallel-plate ionization chamber has a PMMA body, the collector and guard electrodes are made of a thin graphite coating, a 2 mm air gap and a 0.056 cm^3 nominal volume. The polystyrene parallel-plate ionization chamber has a polystyrene body, the collector and guard electrodes are made of a thin graphite coating, a 1 mm air gap and a 0.078 cm^3 nominal volume. Both have an aluminized Mylar entrance window. According to the tests performed by Kubo and Kent (1986), there is no perturbation of the incident charged particle spectrum when using aluminized Mylar as the ionization chamber entrance window. Both ionization chambers were vented to the atmosphere. Table 1 tabulated the physical characteristics of the constructed ionization chambers. A schematic diagram of them is shown in Fig. 1.

For most measurements, the ionization chambers were connected to a Keithley model 35617EBS electrometer. For the saturation measurements, a Nuclear Enterprises Ltd (NEL) model 2570 electrometer was used. An NEL model 2571 cylindrical ionization chamber was used as a reference ionization chamber. A Victoreen model 30-404 parallel-plate ionization chamber (Memorial-Holt) was used as a reference ionization chamber as well. The commercially available chambers were calibrated at AAPM Accredited Dosimetry Calibration Laboratory (ADCL), K & S Associates Inc., Tennessee, U.S.A.

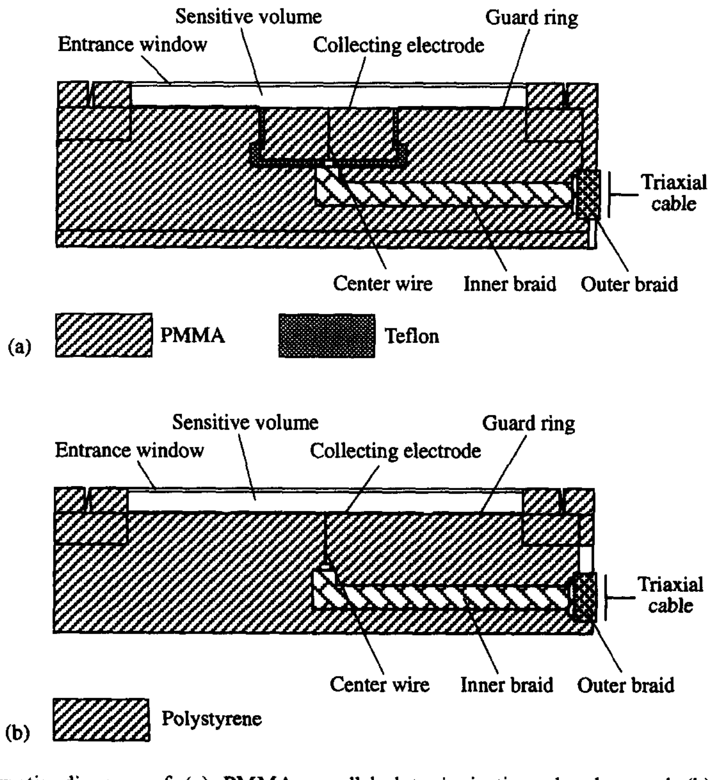

Fig. 1. Schematic diagram of (a) PMMA parallel-plate ionization chamber and (b) polystyrene parallel-plate ionization chamber.

Electrons of 6, 9, 12, 16 and 20 MeV from a Varian Clinac 2100C linear accelerator were used in this study. A Theratronics Theratron T-1000 cobalt-60 irradiator was also used.

For most of the tests, the ionization chambers were irradiated at 100 cm source–surface distance (SSD), except for the angular dependence test where a 110 cm SSD was used.

3. RESULTS AND DISCUSSION

The ionization chambers were submitted to the following tests: short- and long-term stability, leakage, ion collection efficiency, angular dependence, polarity and cable effects. The ionization chambers were calibrated by comparison with a cylindrical ionization chamber in a 20 MeV electron beam and a cobalt-60 gamma ray beam. The replacement correction factor was measured as well.

3.1. *Short- and long-term stability tests*

For the short-term stability test, 10 consecutive readings, corrected for ambient conditions, were taken on each occasion for both ionization chambers using a cobalt-60 irradiator. The percentage standard deviation values for both ionization chambers were less than $\pm 0.5\%$ for all trials.

For the long-term stability tests, a series of measurements were performed using the cobalt-60 irradiator in a reproducible geometry: field size $10 \times 10\ cm^2$, SSD = 100 cm and depth = $5\ g\ cm^{-2}$. In the case of the PMMA chamber this test lasted 20 months and in the case of the polystyrene chamber 11 months. Figure 2 shows the variation in relation to the mean value of the chamber response as a function of the measurement number for the ionization chambers of PMMA and polystyrene, respectively. As can be observed, all mean values for both ionization chambers lie within $\pm 1\%$.

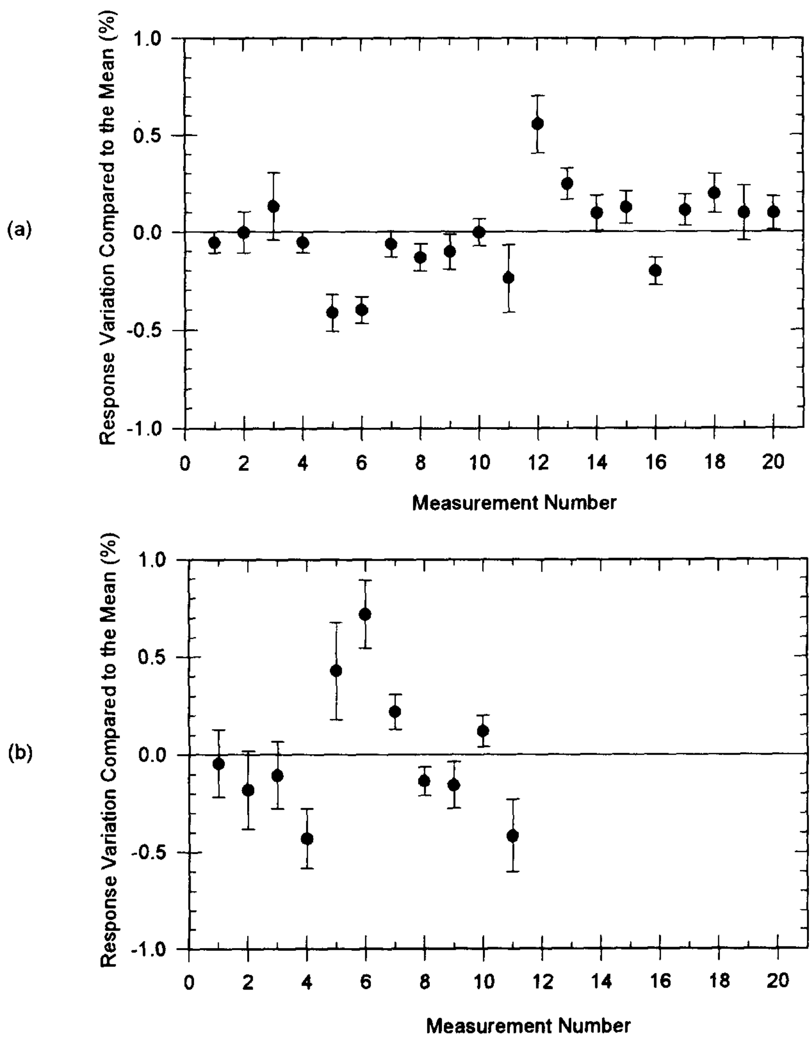

Fig. 2. Long-term stability test of the parallel-plate ionization chambers: (a) PMMA ionization chamber; and (b) polystyrene chamber. Each data point represents the mean of 10 readings.

For both tests, the chamber results are within the recommended values (IEC, 1982) for a field instrument (±1%).

3.2. *Leakage test*

The pre-irradiation leakage current was less than 5×10^{-15} A for both ionization chambers. The post-irradiation leakage test verified that the signal current became less than 0.5% 5 s after the beam was turned off (IEC, 1982).

3.3. *Ion collection efficiency*

The graphical method was used to determine the ion collection efficiency for the parallel-plate ionization chambers. In this method, the graphs which relate current (i) and voltage (V) as $1/i$ versus $1/V^2$, for continuous radiation (Boag, 1966), and as $1/i$ versus $1/V$, for pulsed radiation (Boag and Currant, 1980), permit the calculation of the value of saturation current extrapolating $1/V$ or $1/V^2$ toward zero. Figure 3 presents the ion collection efficiency for both ionization chambers as a function of the voltage, for a 20 MeV electron beam at a dose rate of 400 cGy min^{-1}. Similar results were also obtained for other electron energies. The ion collection efficiency for these conditions were 99.4 and 99.6% for the PMMA and polystyrene ionization chambers, respectively. For the cobalt-60 gamma radiation, the ion collection efficiency was better than 99.9% for both ionization chambers for a dose rate of 100 cGy min^{-1}.

3.4. *Angular dependence*

In this case, a cylindrical ionization chamber was used as a reference chamber, because its response is isotropic in the direction perpendicular to its axis. The relative response Δ% was defined as:

$$\Delta\% = 100\frac{(R_{pp} - R_{cyl})}{R_{cyl}} + 100, \qquad (1)$$

where R is the ratio between the response for any incident angle and for the incident angle of 0° for each chamber, and the subscripts 'pp' and 'cyl' indicate the parallel-plate and cylindrical ionization chambers, respectively.

Figures 4 and 5 show the angular dependence of the parallel-plate ionization chambers in PMMA and polystyrene, respectively, obtained for the 6 and 20 MeV electron beams. The maximum standard deviation for these results was 0.3%. For the PMMA chamber, the angular limit for use is 25°, where the response variation is less than 1% (IEC, 1982). For

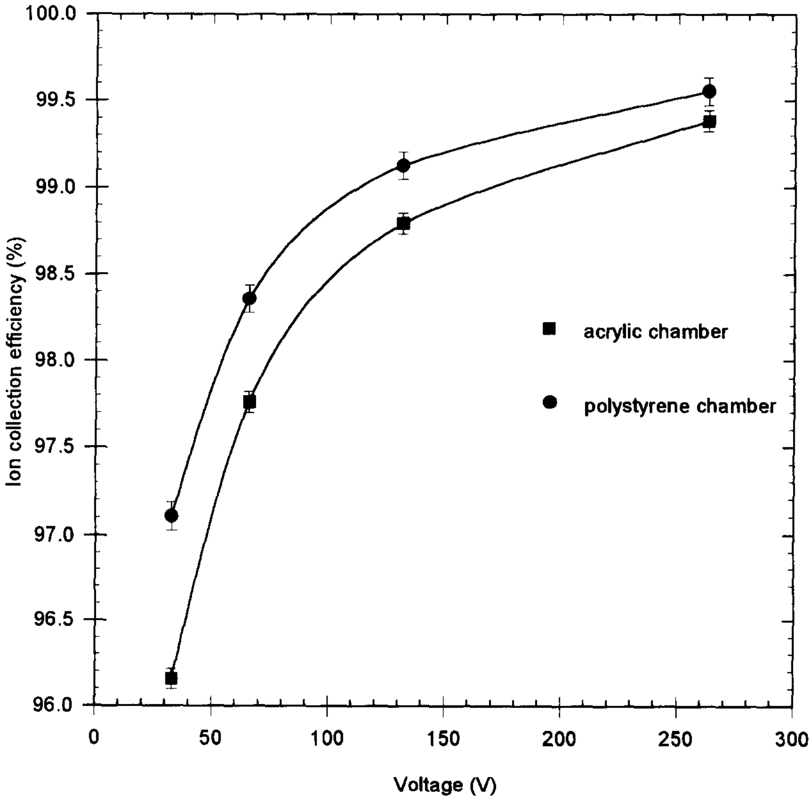

Fig. 3. Variation of ion collection efficiency, determined by graphic method, as a function of voltage for the 20 MeV electron beam for the PMMA and polystyrene ionization chambers at a dose rate of 400 cGy min^{-1}.

(a)

(b)

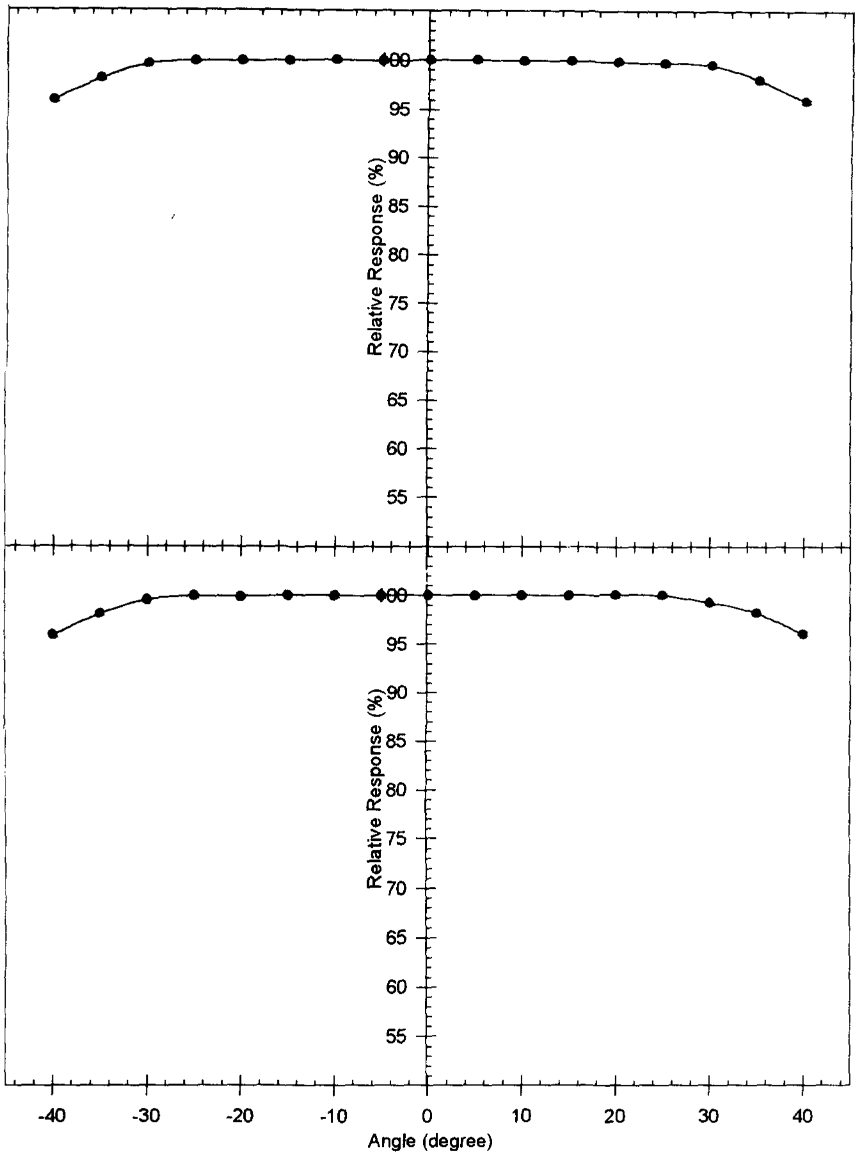

Fig. 4. Angular dependence for the polystyrene parallel-plate ionization chamber for (a) 6 MeV and (b) 20 MeV electron beams.

the polystyrene chamber this angular limit is approximately 30°.

3.5. *Polarity effect*

All the readings at one chamber bias were taken first. The polarity was then reversed and all the readings at the opposite bias were taken using the same experimental arrangement. A minimum of five minutes was allowed to elapse between polarity reversals in order to allow the chamber to equilibrate to the new bias setting. The polarity effect was defined as:

$$F_{pol} = \frac{2|Q_+|}{|Q_-| + |Q_+|}, \qquad (2)$$

where $|Q_-|$ and $|Q_+|$ are the readings at negative and positive polarities, respectively.

Figures 6 and 7 show the polarity effect for both ionization chambers as a function of depth for 6, 9 and 20 MeV electron beams. The polarity effect tends to increase with depth and is less for higher energies. Figure 8 shows the polarity effect for the commercial parallel-plate ionization chambers in a 9 MeV electron beam (Gerbi and Khan, 1987). Readings are calculated as $|Q_-|/|Q_+|$. The results of the constructed ionization chambers are similar to the commercially available ionization chambers and they are within the recommended value (AAPM, 1994).

3.6. *Cable effect*

According to Humphries and Purdy (1992), the effect of cable irradiation is canceled when the mean of readings obtained at opposite polarities is assumed to be the correct reading. Therefore, the effect of cable irradiation was tested assuming the real response, Q_{real}, of the ionization chambers as:

$$Q_{real} = \frac{|Q_-| + |Q_+|}{2}. \quad (3)$$

The ionization chambers were irradiated in rectangular fields of 6 × 25, 10 × 25, 15 × 25 and 20 × 25 cm². The following two conditions: (i) protected cable and (ii) non-protected cable were tested. In the first condition, the cable was positioned perpendicular to the largest side of the irradiation field. In the second condition, the cable was positioned parallel to the largest side of the irradiation field. For both situations, the ionization chambers were placed at the depth of maximum dose (d_{max}) for each electron beam energy.

For both ionization chambers, these conditions produced differences within 0.5% for Q_{real}.

3.7. *Calibration of the parallel-plate ionization chambers*

The most direct method for determining the cavity-gas calibration factor for parallel-plane ionization chambers employs an intercomparison procedure with a National Institute of Standards and Technology (NIST)-traceable calibrated cylindrical chamber irradiated in a high-energy electron beam under known geometry. The calibration is made using a phantom. The point of measurement for each

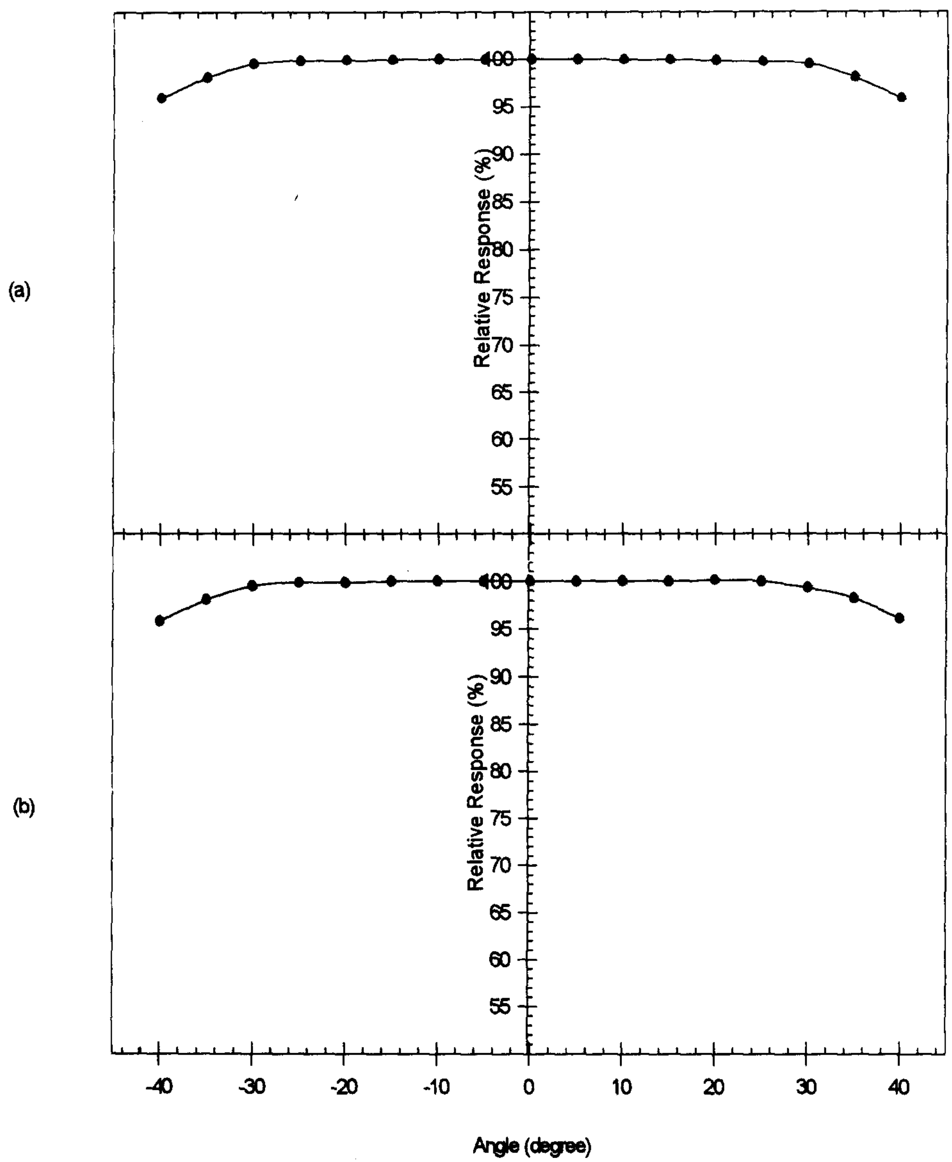

Fig. 5. Angular dependence for the PMMA parallel-plate ionization chamber for (a) 6 MeV and (b) 20 MeV electron beams.

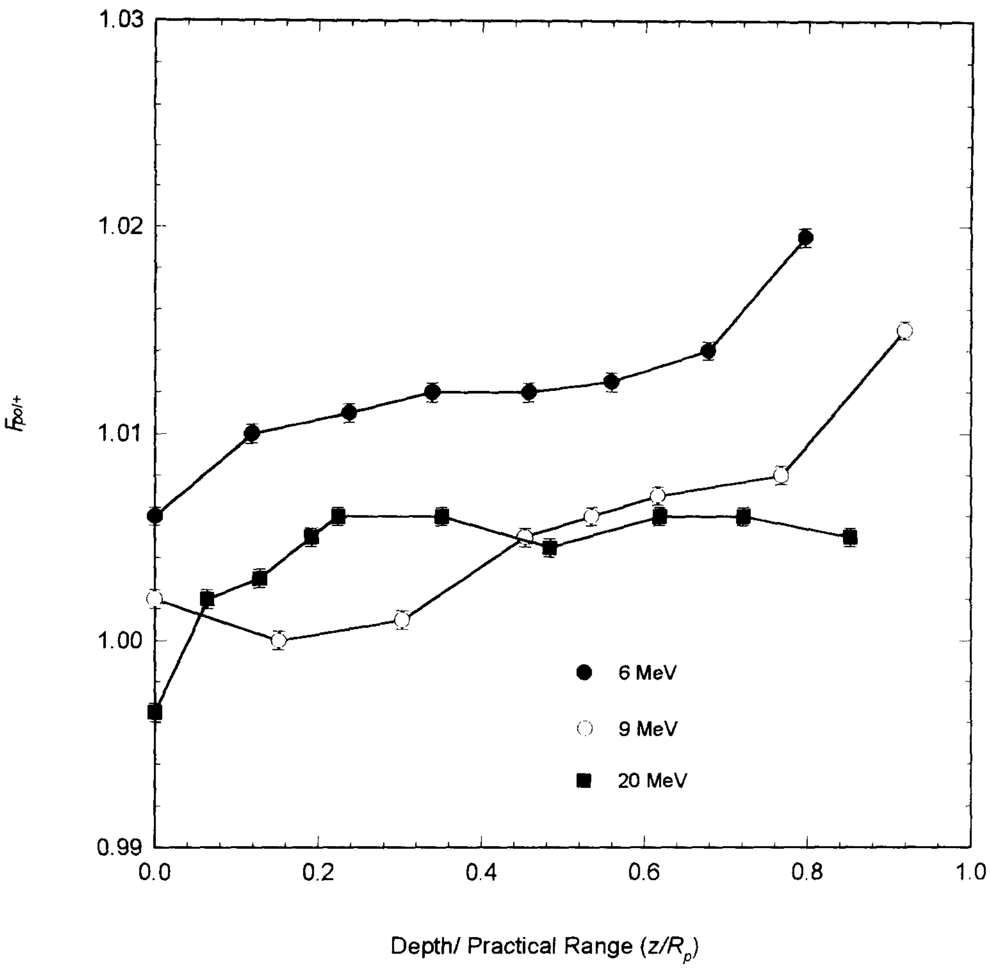

Fig. 6. Polarity effect for the PMMA parallel-plate ionization chamber for different electron beam energies.

chamber was taken as the center of the cylindrical ionization chamber and as the inner surface of the entrance window of the parallel-plate ionization chamber. The point of measurement of each chamber is located at d_{max} and the field size is measured at the phantom surface (AAPM, 1994).

Two other methods, that employ a Cobalt-60 gamma radiation beam, may be used. In one case, the calibration of the parallel-plate ionization chamber is performed in air with a fixed source-to-detector distance (SSD) and the field size (FS) measured at the surface, with the point of measurement taken as the active volume center. Build-up caps are required for both ionization chambers. In the other method, the calibration of the parallel-plate ionization chamber is made in a phantom at a certain depth. The cylindrical and parallel-plate ionization chambers are placed in phantoms at a depth of 5 g cm^{-2}. The point of measurement is also taken as the center of the cylindrical ionization chamber and at the inner surface of the entrance windows of the parallel-plate ionization chamber. However, for the calibration methods in air and in the phantom, the correction factors A_{wall} and P_{wall} are required (AAPM, 1994).

The parallel-plate ionization chambers were calibrated in a phantom through intercomparison with an NIST-traceable calibrated cylindrical chamber at d_{max} for a 20 MeV electron beam and at 5 g cm^{-2} depth for gamma rays of a Cobalt-60 irradiator. In both cases, the phantom material matched the chamber material. The Memorial-Holt parallel-plate ionization chamber was also used for comparison with the constructed ionization chambers. This parallel-plate ionization chamber was calibrated by comparison with the cylindrical ionization chamber in a 20 MeV electron beam and cobalt-60 gamma radiation beam. Additionally, the exposure calibration factor, N_x, provided by AAPM ADCL, was also used to determine the cavity-gas calibration factor, N_{gas}, for this chamber.

A 15 × 15 cm^2 cone size and a 10 × 10 cm^2 field size were used for the electron beam and for the cobalt-60 gamma radiation, respectively, at 100 cm SSD. The following relation was used to obtain the cavity-gas calibration factor for the parallel-plate ionization chambers:

$$(N_{gas})^{cyl} = \frac{(N_{gas})^{pp}(M \cdot P_{ion} \cdot P_{repl} \cdot P_{wall} \cdot P_{cel})^{cyl}}{(M \cdot P_{ion} \cdot P_{repl} \cdot P_{wall})^{pp}}, \quad (4)$$

where N_{gas} is the dose to the gas in the chamber per electrometer reading; M is the charge collected by the ionization chamber corrected for temperature, pressure and polarity; P_{ion} is the ion recombination correction factor; P_{repl} is the correction factor for the replacement of the phantom; P_{wall} is the correction factor for the chamber wall material being different from the dosimetry phantom; and P_{cel} is the correction factor for the central electrode effect. Table 2 shows the correction factors used for the cylindrical and Memorial-Holt ionization chambers.

Table 3 shows the results for the N_{gas} values of the three parallel-plate ionization chambers. These results represent the mean of three trials in different days. For each trial the maximum variation of the measurements was $\pm 0.5\%$. The overall variation of the measurements was $\pm 0.7\%$ (1σ). For the Memorial-Holt chamber, the differences between calibration factors using the cobalt-60 gamma rays and the 20 MeV electron beam were about 1%, either for N_{gas} determined for cobalt-60 gamma rays in the phantom or N_{gas} calculated from N_x (provided by AAPM ADCL) in air. For the PMMA ionization chamber a difference of 1.4% was obtained from the calibration methods. The polystyrene chamber presented N_{gas} for the cobalt-60 gamma rays beam just 0.5% higher than the value for 20 MeV electrons.

For the Memorial-Holt ionization chamber, the 1% difference for the calibration factors determined with cobalt-60 gamma rays and 20 MeV electrons are within the uncertainty ($1\sigma = 1\%$) of the P_{wall} value recommended by the AAPM Task Group 39 (AAPM, 1994). For the PMMA and polystyrene ionization chambers, these results mean P_{wall} values equal to 1.014 and 0.995, respectively.

3.8. *Determination of the replacement correction*

The energy dependence of the replacement correction factors for the parallel-plate ionization chambers was evaluated. The absorbed dose was determined for 6, 9, 12 and 16 MeV electron beams using the parallel-

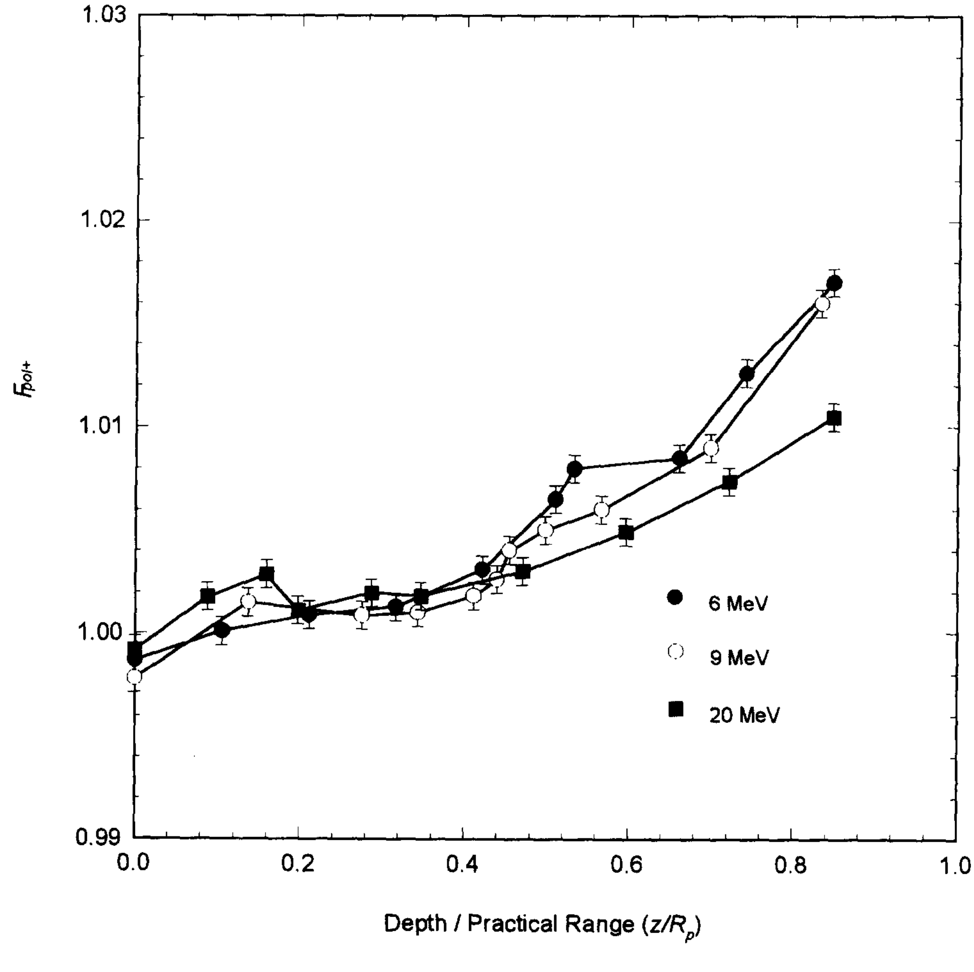

Fig. 7. Polarity effect for the polystyrene parallel-plate ionization chamber for different electron beam energies.

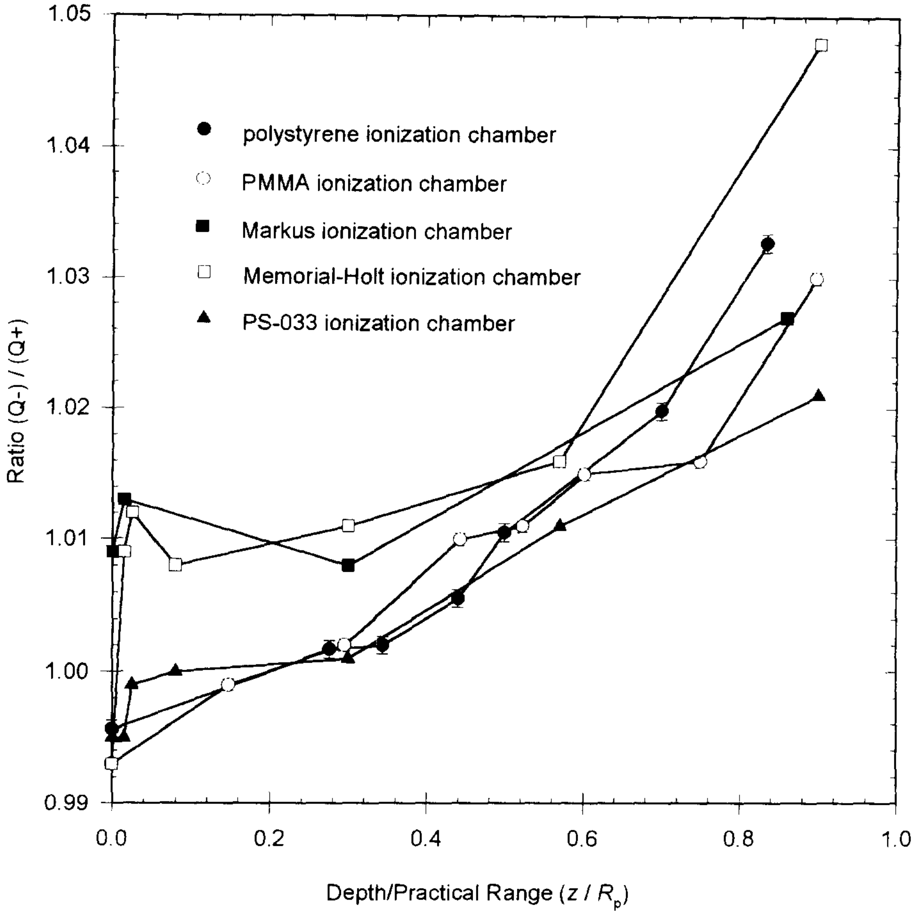

Fig. 8. Ratio between responses at reversal polarities for commercial parallel-plate ionization chambers (Gerbi and Khan, 1987) and for the ionization chambers tested. A 9 MeV electron beam was used.

plate ionization chambers with N_{gas} determined in a 20 MeV electron beam, and with the cylindrical ionization chamber. The following equation was used:

$$(N_{gas})^{cyl} \cdot (M \cdot P_{repl})^{cyl} = (N_{gas})^{pp} \cdot (M \cdot P_{repl})^{pp}, \quad (5)$$

where all factors have the usual meanings. In the case of the cylindrical ionization chamber the P_{repl} values of 0.956, 0.962, 0.972, 0.982 and 0.991 (AAPM, 1983) were used for 6, 9, 12, 16 and 20 MeV electron beams, respectively.

Table 2. Parameter of the cylindrical and plane-parallel ionization chambers used as reference for the Cobalt-60 gamma rays and 20 MeV electron beams

	^{60}Co gamma rays						20 MeV Electrons		
Chamber	A_{wall}	P_{wall}	P_{rep}	P_{cel}	N_x (10^9R/C)	N_{gas} (10^7 Gy/C)	P_{wall}	P_{repl}	P_{cel}
NEL, 2571	0.990	0.988	0.992	1.000	4.748	4.051	1.000	0.991	1.008
Memorial-Holt	1.008	1.000	1.000	1.000	3.201	2.732	1.000	1.000	1.000

Table 3. N_{gas} ($\times 10^7$ Gy C^{-1}) determined for ionization chambers by different calibration methods

	Chamber Memorial-Holt		Chamber Polystyrene		Chamber PMMA	
Calibration Method	N_{gas}	Normalization	N_{gas}	Normalization	N_{gas}	Normalization
In phantom by comparison with NEL 2571 chamber in a ^{60}Co gamma ray beam	2.744	1.010	31.22	1.005	31.71	0.986
In air from N_x provided by ADCL for a ^{60}Co gamma rays beam	2.737	1.008	—	—	—	—
In phantom by comparison with NEL 2571 chamber in a 20 MeV electron beam	2.716	1.000	31.07	1.000	32.15	1.000

Table 4. P_{repl} determined for the parallel-plate ionization chambers

Energy (MeV)	6	9	12	16	20
PMMA ionization chamber	0.995	1.007	1.001	1.004	1.000
Polystyrene ionization chamber	0.998	0.997	0.999	1.000	1.000

Table 4 summarizes the P_{repl} values for the two constructed parallel-plate ionization chambers. The maximum standard deviation (1σ) for these results was $\pm 0.5\%$. Most values were within $\pm 0.5\%$, except in the case of the PMMA chamber in the 9 MeV electron beam, which was within 1%. These results confirm that for parallel-plate ionization chambers with guard ring widths of at least 3 mm, P_{repl} remains practically constant at unity, independently of the range of electron beam energy studied (Mattsson *et al.*, 1981; AAPM, 1983, 1994).

4. CONCLUSION

Two parallel-plate ionization chambers were constructed using the plastic materials recommended for electron dosimetry (AAPM, 1983). The tests performed on the ionization chambers showed that they have good metrological characteristics as field instruments. Both ionization chambers demonstrated applicability for electron beam dosimetry. N_{gas} for the parallel-plate ionization chambers were determined in a high energy electron beam. The obtained P_{wall} values also permit the parallel-plate ionization chambers to be calibrated at some depth in a phantom using a Cobalt-60 gamma ray beam. The P_{repl} factor for both ionization chambers can be considered to be unity within the experimental uncertainties.

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