Determination of overall perturbation factors for plane-parallel ionization chambers in electron beams

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Abstract

Most dosimetry protocols recommend the use of plane-parallel chambers for dose determination in electron beams with energies below 10 MeV. The new IAEA TRS 381 (1997) protocol includes the overall perturbation factor $p_Q$ that consists of the in-scattering correction factor $p_{cav}$ (or $p_{rep}$) and the wall correction factor $p_{wall}$ (or $P_{wall}$). In this work, $p_Q$ for the commonly applied NACP, PTW/Roos and PTW/Markus plane-parallel chambers was determined experimentally. For the NACP plane-parallel chamber, $p_Q$ was obtained by comparison with a cylindrical Farmer chamber, while for the PTW/Roos and PTW/Markus chambers it was obtained by comparison with the NACP chamber. The values of $p_Q$ for these plane-parallel chambers were measured as a function of mean electron energies $\bar{E}_e$ from 1.7 MeV to 11.5 MeV. It was found that for the NACP and PTW/Roos chambers, $p_Q$ is independent of energy down to $\bar{E}_e=1.7$ MeV, while for the PTW/Markus chamber it shows a systematic and exponential drop of about 2% with decreasing energy down to $\bar{E}_e=2.7$ MeV. However, the decrease of $p_Q$ for $\bar{E}_e=1.7$ MeV was not exponential.

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1. Introduction

To determine the absorbed dose in electron beams, especially for mean incident energies below 10 MeV, most dosimetry protocols recommend the use of plane-parallel ionization chambers.\(^1\)\(^5\) This is because these chambers have a good depth resolution and a small fluence perturbation effect. A major source of uncertainty in electron dosimetry with ionization chambers is the perturbation effect introduced by the chamber itself. This effect has two main sources. The first is perturbation of the electron fluence due to insertion of the air cavity with low density into the phantom. This is caused by electrons scattering from the chamber side walls to reach the sensitive volume. This cavity "in-scatter" effect \(p_{\text{cav}}\), called the replacement correction factor \(P_{\text{repl}}\) in the 1983 AAPM protocol,\(^6\) may be an important correction factor if chambers having narrow guard rings are used. The second is the lack of equivalence of the chamber walls to the phantom material. This effect is the wall correction factor \(p_{\text{wall}}\), which has been assumed implicitly to be unity in electron dosimetry protocols to date. In the recent 1996 IPEMB and 1997 IAEA protocols, the product \(p_{\text{cav}}p_{\text{wall}}\) of the two correction factors is expressed as the overall perturbation factor \(p_Q\) (\(p_{\text{cav}}^*p_{\text{ch}}\) in the 1996 IPEMB) since it is difficult to determine \(p_{\text{cav}}\) and \(p_{\text{wall}}\) separately.

To date, several groups have estimated \(p_Q\) for various plane-parallel chambers in electron beams, and it appeared that for some of these chambers \(p_Q\) is energy dependent, differing considerably from unity at lower electron energies.\(^7\)\(^-\)\(^16\) Recently, recommended values for \(p_Q\) of several plane-parallel chambers were given in the 1994 AAPM and 1997 IAEA protocols, and it was shown that for some chambers with an energy dependence, \(p_Q\) is very close to unity for the mean energies above 15 MeV.

The purpose of this work was to experimentally determine values of \(p_Q\) for the commonly applied NACP, PTW/Roos and PTW/Markus plane-parallel chambers in electron beams. In particular, the \(p_Q\) values for mean energies below 10 MeV were measured by comparisons among these plane-parallel chambers to minimize systematic errors, and the results were evaluated against recommended values of the 1997 IAEA protocol.

2. Instruments and methods

A. Measurement conditions

Schematic diagrams of the measurement setups are illustrated in Fig. 1. The physical characteristics of the reference cylindrical Farmer and plane-parallel chambers used are listed in Tables 1 and 2, respectively. \(p_Q\) for the NACP chamber (Scanditronix, Dosetek (Calcam)) was determined by comparison with the cylindrical Farmer chamber, while for the PTW/Roos and PTW/Markus chambers it was determined by compared with the NACP chamber. For these plane-parallel chambers, \(p_Q\) was measured as a function of mean electron energies from 1.7 MeV to 11.5 MeV. Most dosimetry protocols recommend the use of an acrylic phantom (PMMA) for these chambers, to produce minimal perturbation in the electron field. In this work, however, we used a Solid Water phantom (Model 457, RMI-Gammex Inc., Middleton, WI 53562) since Solid Water is water equivalence compared to
PMMA and equivalent to PMMA with respect to backscatter within the experimental uncertainties of electron beams.\textsuperscript{17-18)} The effective point of measurement for the Farmer chamber was taken at 2/3 of an inner radius proximal to the chamber axis, while for the plane-parallel chambers it was the inner surface of the entrance window.

The therapy instruments used were a Mitsubishi EXL-15 DP with 4-15 MeV electron energies and a Varian Clinac 2100C with 4-16 MeV electron energies. For all charge measurements, a RAMTEC 1000 Dose-Dose Rate Meter (Toyo Medic Co., Ltd, Osaka, Japan) and a Victoreen Model 500 Precision Medical Physics Electrometer (Victoreen Inc., Cleveland, Ohio) were used. The charge measurements were taken with positive and negative polarities, and the average value was used to determine $p_Q$. The results of the polarity effect are also described below. The ion recombination correction factors $p_s$ for the plane-parallel and Farmer chambers were determined by the two-voltage method.\textsuperscript{19-20) All the measurements required the charge ratios between the plane-parallel chamber and the reference Farmer or NACP chamber. A series of measurements was repeated at

\begin{table}[h]
\centering
\caption{Physical characteristics of the cylindrical Farmer chamber.}
\begin{tabular}{lcccc}
\hline
Chamber & Wall & Buildup cap & Cavity dimensions & Central electrode & $k_{un} k_m$
\hline
0.6 cm$^3$ Farmer$^a$ & PMMA & 0.045 & PMMA & 0.541 & 22.0 & 6.1 & aluminun$^b$ & 0.972
PTW 30001 & & & & & & & & \\
\hline
\end{tabular}
\end{table}

$^a$Physikalisch Technische Werkstätte.
$^b$Diameter: 1mm.
least three times on different days to make sure that the ratios did not fluctuate by more than 1.0% in day-to-day operation. The charge measurements were also continued until the last three readings were within ±0.2% to minimize systematic errors.

B. Determination of the overall perturbation factor

For the NACP chamber $p_Q$ was obtained from comparison with the Farmer chamber at a reference depth $z_{ref}$ with maximum ionization in the Solid Water phantom, to minimize the uncertainty for the effective points of measurement of the chambers. If $p_Q$ for the NACP chamber is taken to be unity for 16 MeV with the highest electron-beam energy available in this work, it can be obtained from the following relation:

$$p_{Q,E}^{NACP} = \frac{[M_p \cdot \phi_{cav}^{E}]_{16E}^{NACP,E}}{[M_p \cdot \phi_{cav}^{E}]_{16E}^{NACP,16E}}.$$  

$p_{wall}$ for the Farmer chamber was taken to be unity for all electron beams used in this work. On the other hand, $p_Q$ for the PTW/Roos and PTW/Markus chambers was obtained from comparison with the NACP chamber at $z_{ref}$, and it is given by

$$p_{Q,E}^{PP} = \frac{[M_p \cdot \phi_Q]_{NACP,16E}^{NACP,E}}{[M_p \cdot \phi_Q]_{16E}^{PP,E}}.$$  

where $M$ is the measured charge corrected for temperature, pressure, and polarity effect. The symbols cyl and pp indicate the cylindrical and plane-parallel chambers, respectively. The mean electron energy $E_z$ at $z_{ref}$ (a depth of 1.5 cm) for 16 MeV electrons was 11.5 MeV, thus the value of $p_{Q,16E}$ for the PTW/Markus chamber was taken to be 0.999 from the 1997 IAEA protocol. For the PTW/Roos chamber $p_{Q,16E}$ was taken to be unity. In this work, $p_Q$ for plane-parallel chambers was determined with the normalization of the response quotients obtained in 16 MeV ($E_z=11.5$ MeV) electrons, as shown in Eqs. (1) and (2).

All of the measurements were made in phantoms with a source-surface distance of 100 cm and
Table 3 Electron beam parameters for a 15 × 15 cm² irradiation field defined at a source-surface distance of 100 cm. The values of \( E_0 \), \( E_z \) and \( \rho_{\text{ex}}^{\text{rel}} \) are obtained from the IAEA (1997) protocol.

<table>
<thead>
<tr>
<th>Nominal energy (MeV)</th>
<th>( z_{\text{ref}} ) (cm)</th>
<th>( R_{\text{so}} ) (cm)</th>
<th>( R_{\phi} ) (cm)</th>
<th>( E_0 ) (MeV)</th>
<th>( E_z ) (MeV)</th>
<th>( \rho_{\text{ex}}^{\text{rel}} )</th>
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</thead>
<tbody>
<tr>
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<td>15.0</td>
<td>9.2</td>
<td></td>
</tr>
</tbody>
</table>

\( a \)Reference depth \( (z_{\text{ref}} \) is taken at a depth of maximum ionization in this work).

\( b \)Depth of 50% ionization.

\( c \)Almost maximum ionization.

the effective points of measurement for each chamber placed at \( z_{\text{ref}} \). A 15 × 15 cm² field defined at the phantom surface was used at nominal electron energies from 4 MeV to 16 MeV. The electron beam parameters given in Table 3 were obtained from the measured depth-dose or depth-ionization distribution. Following the 1997 IAEA protocol, the mean incident energy \( E_0 \) was calculated from the following polynomial:

\[
\bar{E}_0 [\text{MeV}] = 0.818 + 1.935 R_{\text{so}}^1 + 0.040 (R_{\text{so}}^1)^2
\]  (3)

where \( R_{\text{so}}^1 \) (in cm) is the depth of the 50% ionization in water. The mean energy at depth \( z \), \( \bar{E}_z \) for a water phantom and the perturbation factor \( \rho_{\text{ex}}^{\text{rel}} \) for the Farmer chamber were also obtained from Tables 11 and 12 of the 1997 IAEA protocol, respectively.

All the data were read in about 1.00 Gy (100 MU) at a dose rate of 4.00 Gy/min, for both positive and negative polarities. The average value of \( \rho_s \) ranged from 1.005 to 1.009 for the Farmer chamber and from 1.003 to 1.005 for the plane-parallel chambers.

3. Results and discussion

A. Polarity effect

In Fig. 2 the polarity effect is shown as a function of the mean electron energy for the plane-parallel chambers. All the measurements were performed at \( z_{\text{ref}} \). The polarity effect is defined here as half the difference in the absolute values of the readings with positive and negative polarities divided by the mean value as follows:
\[
\frac{\Delta M}{M} = \frac{|M_+| - |M_-|}{|M_+| + |M_-|}
\] (4)

where \( M_+ \) and \( M_- \) are the measured charges in positive and negative polarities, respectively. The effect of the NACP chamber increased with increasing electron energy, but it was within \(+0.2\%\). The PTW/Roos chamber showed a polarity effect of less than \(\pm0.1\%)\, and it was energy independent. The effect for the Markus chamber was negligible for mean energies above 0.9 MeV, but it increased with decreasing electron energy. The deviations for the mean energy range 2 to 4 MeV were about -0.5% to -1.0%, and the polarity effect was slightly smaller at the mean energy of 1.7 MeV than 2.7 MeV. A reason for this is not obvious but it may be caused by the decrease of electrons scattering from the chamber side walls to reach the sensitive volume at \(E_0=1.7\) MeV. Thus, for the Markus chamber the polarity effect should be considered in the case of low electron energies. The polarity effect for the Farmer chamber was within \(\pm0.1\%)\ across the electron energy range used in this work (not shown in Fig. 2).

B. Determination of the overall perturbation factor

In Figs. 3 and 4 \(\rho_Q\) values are given as a function of the mean electron energy for the plane-parallel chambers. The error bars represent one standard deviation (1 s.d.), derived by quadratic summation of the statistical uncertainties of the values measured in each mean energy and \(E_0=11.5\) MeV. As expected, the \(\rho_Q\) values for the NACP chamber were very close to unity in the measured electron energy range. The \(\rho_Q\) values obtained from the Mitsubishi EXL-15DP showed a larger standard deviation than with the Varian Clinac 2100C because of fluctuations in beam energy and output. The deviations from unity of the \(\rho_Q\) values were within \(\pm0.4\%)\ in comparison with the Farmer chamber for mean energies from 2.7 MeV to 11.5 MeV. However, they are within the limits of experimental uncertainty when the uncertainties of \(\rho_{\text{var}}\) for the Farmer chamber and fluctuations in beam energy and output of linear accelerators are taken into consideration. Thus, \(\rho_Q\) for the NACP chamber was taken to be unity for all the electron energies in comparison with the PTW/Roos and PTW/Markus chambers, and the more stable Varian Clinac 2000C in beam energy and output was used.

The \(\rho_Q\) values for the PTW/Roos chamber were in good agreement with the NACP chamber, and the deviations were within \(\pm0.1\%)\ down to \(E_0=1.7\) MeV. These results show that the chamber perturbation factor is equal to unity if the guard ring widths are greater than 3 mm for a cavity thick-
Fig. 3 $p_Q$ values for the NACP chamber as a function of the mean electron energy, measured by comparison with the Farmer chamber. The error bars represent 1 s.d.

Fig. 4 $p_Q$ values for the PTW/Roos and PTW/Markus chambers as a function of the mean electron energy, measured by comparison with the NACP chamber. The dashed line represents the exponential curve fitting through the data of Van der Plaetse et al.\textsuperscript{15} The chain line is drawn at $p_Q = 1.00$ for the NACP chamber. The error bars represent 1 s.d.

ness of 2 mm, as presented by Mattsson et al.\textsuperscript{21} and the 1997 IAEA protocol. On the other hand, the $p_Q$ values for the Markus chamber were close to unity with higher energy electrons, but they varied considerably with lower energy electrons. The magnitude of variation increased generally as energy decreased, and it deviated by 2.0% in the vicinity of $E_z = 2$ MeV. In Fig. 4 the dashed line represents the exponential curve fitting through the data of Van der Plaetse et al.\textsuperscript{15} adapted in the 1996 IPEMB and 1997 IAEA protocols. Our results were in good agreement with those of Van der Plaetse et al. down to $E_z = 2.7$ MeV. Against expectations, however, the $p_Q$ value for $E_z = 1.7$ MeV did not show an exponential decrease, and this chamber behaved very similarly to the PTW/Schulz chamber at lower energies.\textsuperscript{5} A reason for this may again be the slight decrease of electrons scattering from the chamber side walls at $E_z = 1.7$ MeV compared to $E_z = 2.7$ MeV, as shown in the polarity effect for the Markus chamber. Finally $p_Q$ for $E_z < 2$ MeV may involve an uncertainty even in the plane-parallel chambers since the plateau of maximum dose can hardly be observed. In determination of $p_Q$ for $E_z < 2$ MeV, it is therefore recommended to make comparisons with a thin-walled extrapolation chamber having a large guard width.\textsuperscript{22}

4. Conclusions

From this work, we concluded that $p_Q$ for the NACP and PTW/Roos chambers is independent of the electron energy because the guard rings are sufficiently wide, while the PTW/Markus chamber is energy dependent because its guard ring width is narrow. Our results for the Markus chamber...
were in good agreement with the recommended data of the IAEA TRS-381 (1997) protocol down to \( E_\gamma = 2.7 \) MeV, and they showed an exponential decrease. However, the decrease of \( \rho_Q \) for \( E_\beta = 1.7 \) MeV was not exponential. The PTW/Roos chamber also had the smallest polarity effect, and therefore it may be most suitable for electron dosimetry with plane-parallel chambers.

References
13) Kuchnir FT and Reft CS: Experimental values for \( P_{\text{wall,x}} \) and \( P_{\text{repl,E}} \) for five parallel-plate ion